Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 4869-4879

ECCOMAS
Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

COMPARATIVE ASSESSMENT OF EMPIRICAL AND MECHANICAL APPROACHES FOR THE ESTIMATION OF THE SEISMIC FRAGILITY OF ORDINARY MASONRY BUILDINGS TYPE OF THE INNER CENTRAL ITALY

Ilaria Capanna[1], Franco Di Fabio[2], and Massimo Fragiacomo[2]

[1] Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila, Monteluco di Roio, 67100, L'Aquila, Italy
e-mail: ilaria.capanna@graduate.univaq.it

[2,3] Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila, Monteluco di Roio, 67100, L'Aquila, Italy
{franco.difabio, massimo.fragiacomo}@univaq.it

ABSTRACT

The assessment of the built heritage vulnerability is a needful task to mitigate the seismic risk. At this aim, fragility functions estimate the probability of exceedance of a structure at discrete levels of ground motion. The paper focuses on the estimation of seismic fragility of unreinforced masonry buildings typical of the inner Central Italy. Fragility assessments were performed for selected ordinary buildings representative of the urban fabric of the Central Italy, hit by the 2016 earthquake recently. The buildings' stock belongs to a macro-typology defined by structural features, easily available from visual inspections and geometric surveys. The structural performances of the buildings are assessed by means of empirical and numerical approaches, based on a large portfolio of information gathered after the 2016 earthquake swarm. Lastly, the fragility curves for the macro-typology have been derived referred to the attainment of four limit states of interest. A comparison between the obtained results in terms of probabilities of exceedance underlines the main advantages and limitations of each approach in the seismic vulnerability prediction on large scale applications.

Keywords: Masonry un-reinforced buildings, fragility curves estimation, vulnerability assessment, damage scenarios.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8834.18980

1 INTRODUCTION

Recurring earthquakes in seismic prone areas represent a serious threat for the built environment due to structural vulnerabilities that affect the existing buildings. Particularly, masonry constructions suffer extended damage up to lose their structural stability under an earthquake action. Thus, in recent years, a growing attention has been reserved to the evaluation of the structural vulnerability of existing buildings, also deepened by fragility assessment, to mitigate the seismic risk. A fragility function specifies the probability of a structure of attainment or exceedance a limit states of interest, depending upon a certain ground motion intensity measure [1].

About the estimation of the fragility functions, a significant part of the scientific literature focuses on the derivation of fragility curves based on simplified analysis methods or alternative definition of the limit states [2, 3].

Several approaches are used to derive fragility curves: empirical, analytical and hybrid. Empirical fragility methods aim to predict damage for specific levels of ground motion intensity based on post-earthquake damage data of specific building typologies [4,5,6], through simplified assessment of seismic performance. Analytical methods, also called mechanics-based methods, define the fragility functions based on structural or analytical models that appraisal the seismic behaviour of the structure [7,8]. Limit state are defined in terms of quantitative measure of structural performance, like displacements and deformation indicators [9,10]. Hybrid methods derive fragility curves using features of empirical and mechanics-based methods.

The reliability of each method depends on the availability of data and its accuracy.

Empirical fragility assessment is calibrated on a specific area hit by an earthquake. In general, empirical fragility curves reflect uncertainties on structural data and ground shaking intensity. Analytical fragility assessment requires a numerical or mechanical model of the structure based on an in-depth knowledge of mechanical parameters and structural details, difficultly achievable at territorial scale application.

This paper aims to compare the empirical and numerical approaches to derive fragility curves for ordinary masonry buildings, located in the inner Central Italy, recently hit by a shattering seismic swarm. The investigation of the seismic behavior of these buildings attempts to mirror the entire class, representative of the local built-up.

The mean damage of the buildings' class was, in accordance with the European Macro seismic Scale classification, EMS-98, through an empirical approach proposed by the authors, to derive fragility curves for five damage states. After that, the fragility functions were estimated from the results of non-linear static analysis. A comparison between the typological empirical fragility curves and numerical ones reveals the main advantages and limitations in forecast damage scenarios and supporting resilience-enhancing strategies.

2 DESCRIPTION OF THE CASE STUDY

2.1 Characterization of the case study

The Italian built environment exhibits typical features for each region, in terms of materials and structural configurations, requiring a classification at local or regional scale [11]. This paper deserves attention to the seismic performance of the masonry ordinary buildings typical of the Central Italy, hit by the last seismic swarm occurred in the 2016. The proposed methodology can be addressed to any buildings' typology by considering structural features of the analyzed facilities, as done by other authors [12,13].

The prevalent typologies of the analyzed built-up consist of low-rise masonry buildings and reinforced-concrete frame buildings. Regarding the masonry facilities, two main typologies could be detected in the selected geographical area: (i) historical constructions and (ii) ordinary buildings. Buildings (i) are located in the historical centers, often built attached to each other up to compose masonry aggregates of structural units with different height, number of stories, structural types and materials heterogeneities [14,15]. In general, historical buildings are conceived to withstand only gravity loads: under an earthquake action, they suffer local mechanisms, like out-of-plane response of masonry walls. Buildings (ii), built in the last century to expand urban centers, follow the empirical rules and the code dispositions in force at the construction period. Most of them are endowed of connections wall-to-wall or anti-seismic devices, like iron ties, that ensure a global response of structures. Often though the poor mechanical properties of the masonry give rise to an unsatisfactory seismic performance.

Fifteen masonry buildings are selected as representative of the ordinary buildings' class of the area hit by the 2016 earthquake. Most of these buildings manifested an in-plane seismic response, with typical shear and bending failure modes. Some of them suffered local mechanisms due to the ineffectiveness of the connections wall to wall. The observed damage was estimated in agreement with the damage classification by Grünthal [16] that ranges from the Level 0 to the Level 5.

Buildings with a suffered damage grade D_{k2} consist of 13.33% of the sample; with a damage grade D_{k3} of 80 %, and with a damage grade D_{k4} of 6.67%.

2.2 The Central Italy seismic swarm

In 2016, the Central Italy was hit by a seismic swarm that started on 24 August. The first mainshock, with a magnitude M_w= 6.2, occurred with an epicenter located in Accumoli (Rieti). The second mainshock, with a magnitude M_w=5.5, occurred with an epicenter in Norcia (Perugia). The seismic swarm continued up to 6500 aftershocks with a M_w until 5.5, affecting four regions: Lazio, Abruzzo, Marche and Umbria. The seismic genetic area concerns a complex structural configuration and different faults, see Fig.1 (INGV) [17]: the soil and topographic configurations drove strong local site effects.

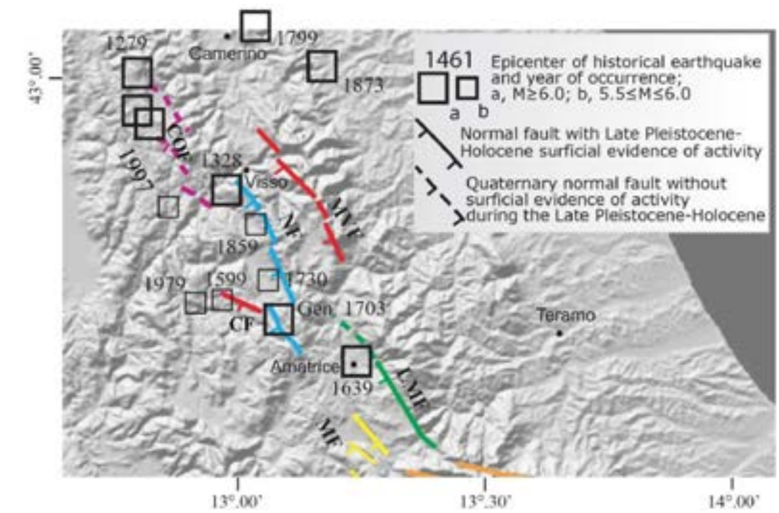

Fig. 1 Scheme of Quaternary and / or active faults in the area between the Montereale basin (south) and the Colfiorito area (north): COF, Colfiorito fault; MVF, fault of the M. Vettore; NF, Norcia fault; CF, Cascia fault; LMF, Monti della Laga fault; MF, faults in the Montereale basin (INGV)

Overall, the seismic swarm was shattering giving rise to hundreds of buildings damaged and un-safe.

3 SEISMIC VULNERABILITY ASSESSMENT

3.1 Seismic assessment by means an empirical approach.

In the last decades, a significant part of the scientific literature focused on the simplified estimation of the seismic vulnerability of masonry buildings [18,19] to face the estimation of the seismic vulnerability at territorial level.

Empirical approaches attempt to overcome the effort of seismic vulnerability assessment on large-scale application resorting to few structural and mechanical parameters, known from visual inspections or geometric surveys.

The authors proposed a simplified method finalized to provide a vulnerability index (ranging from 0 to 100) for the in-plane seismic behavior, based on ten parameters evaluated through quick formulations, related to three classes of growing vulnerability (from A to C), with different scores associated, see Table 1.

	Parameter of the wall	Weight	
1	Quality of the masonry	1.00	Class A: score 0 Class B: score 50 Class C: score 100
2	Amount of openings	0.5	
3	Behaviour in plan	0.8	
4	Behaviour in elevation	0.75	
5	Typology of opening	0.20	
6	Stiffness of the spandrel beams	0.40	
7	Tensional state in plan	0.8	
8	Tensional state in elevation	0.8	
9	Position of the wall	1.25	
10	Site effects	1.05	

Table 1: Form of the proposed predictive method.

The method was applied to each building of the case study. The mean value of the vulnerability indices, representative of the entire buildings' sample, was equal to 43.88. The expected mean damage of the typological class μ_D was estimated using the macro-seismic method [20], according to Equation 1:

$$\mu_D = 2.5\left[1 + tanh\left(\frac{(I+6.25V-13.1)}{Q}\right)\right] \quad (1)$$

Where I is the macro-seismic intensity, Q is a ductile factor set equal 2.3, and V is the normalized vulnerability index representative of the entire class. The average vulnerability curves and the confidence bounds associated are derived for different scenarios, expressed in terms of macro-seismic intensity, in Fig.2 (a), and in terms of peak ground acceleration in Fig.2 (b), evaluated according to Murphy O'Brien law correlation [21].

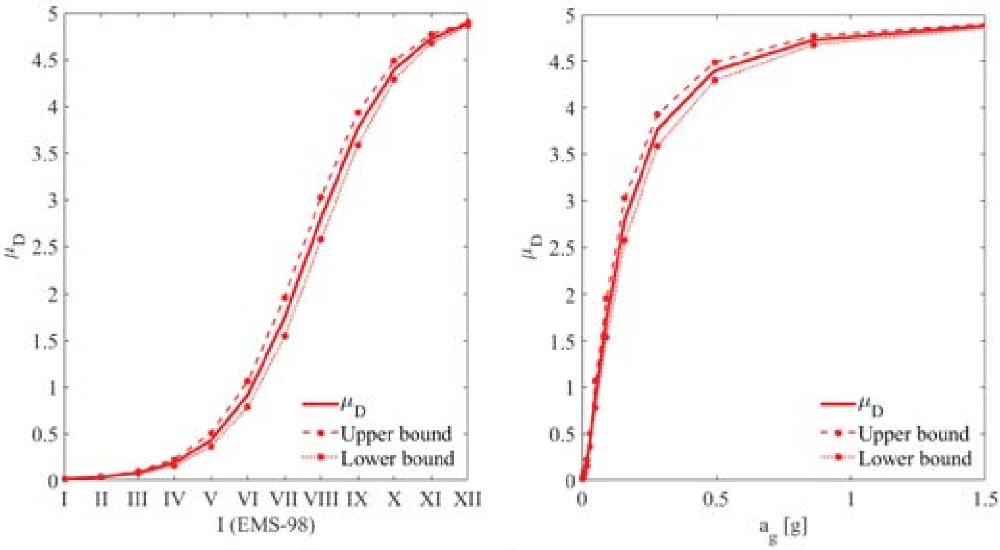

Fig. 2. Mean typological damage curves: in terms of Intensity Measure (a); in terms of a_g (b).

The probability of occurring the damage grade D_k is estimated as a function of the μ_D according to the Eq. 2, [16]:

$$p_k = \frac{5!}{k!(5-k!)}\left(\frac{\mu_D}{5}\right)^k\left(1-\frac{\mu_D}{5}\right)^{5-k} \quad (2)$$

The typological fragility curves, derived by means the empirical method, are plotted in Fig.3: expressed in terms of macro-seismic intensity, in Fig.3 (a), in terms of peak ground acceleration in Fig.3 (b).

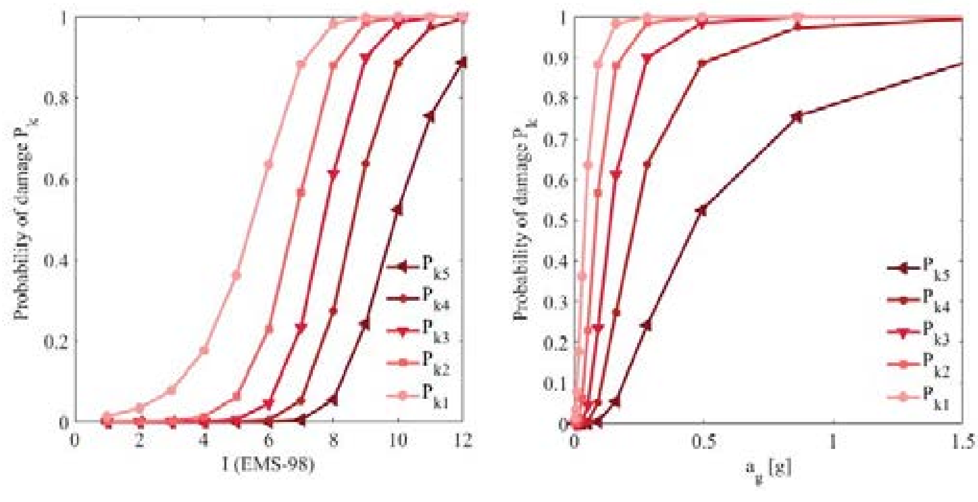

Fig. 3. Typological fragility empirical curves: in terms of Intensity Measure (a); in terms of a_g (b)

3.2 Seismic assessment by means mechanical approaches.

Mechanics-based approaches appraisal the seismic structural performance of buildings accurately based on a numerical or analytical modeling. The achievement of a reliable estimation of the seismic behavior of a structure requires a deep knowledge of the structural system, detailed data, in-situ diagnostic tests, and a high computational effort. Therefore, the mechanical estimation of the seismic performance at territorial level represents a tricky application.

Nevertheless, the authors derived the fragility curves of the class through numerical analysis to compare the different approaches.

Static no linear analysis was performed using a commercial software package, 3Muri software [22], in which the equivalent frame modelling is implemented. The seismic action corresponds to the design response spectrum, defined to the spectral parameter a_g (max acceleration value), F_0 (max value of the amplification factor for the horizontal acceleration response spectrum) and T_c^* (period of the horizontal onset for constant velocity), according to the Italian Seismic Code [23, 24]. The response spectrum is defined for a return period, Tr, of 30 years, for Operational Limit State, LS1; 50 years, for Damage Limit State, LS2; 475 years, for Significant Damage Limit State, LS3; 975 years, for Collapse Limit State, LS4. Non-linear static analyses were carried out along the longitudinal and transversal direction, by applying two different seismic loads, and an accidental eccentricity between the mass centroid and the stiffness centroid is considered, according to the Italian Design Code. The Acceleration Displacement Response Spectrum, ADRS, was assumed to evaluate the seismic capacity and demand of the structure [25]. Twenty-four pushover analyses were performed from each of the fifteen buildings, yielding 360 analysis.

Still, for each structure, the analysis representative of the lowest safety level.

The probability of collapse, P_c, descends from the estimation of the standard normal cumulative distribution function Φ, as expressed in Equation (3):

$$P[d_s|S_d] = \Phi\left[\frac{1}{\beta_s}\ln\left(\frac{S_d}{\bar{S}_{ds}}\right)\right] \quad (3)$$

Where d_s is the displacement of the threshold of damage state, S_{ds} is the median value of spectral displacement at d_s, $ß_s$ is the standard deviation of the natual logarithm of spectral displacement of a damage state d_s. The limit damage thresholds are reported in Table 2:

Damage Limit State		Displacement Limit State
LS1	Operational Limit State	$0.7 \cdot d_y$
LS2	Damage Limit State	$0.8 \cdot d_y + 0.2 \cdot d_u$
LS3	Significant Damage Limit State	$0.5 \cdot (d_y + d_u)$
LS4	Collapse Limit State	d_u

Table 2: Damage thresholds definition.

The yielding and ultimate displacement, d_y and d_u, correspond to the average of the fifteen values, equal to 0.003 m and 0.011 m, respectively. The standard deviation is equal to 0.15 for the yielding displacement and 0.39 for the ultimate displacement. The typological fragility curves derived by means the numerical method are plotted in Fig. 4.

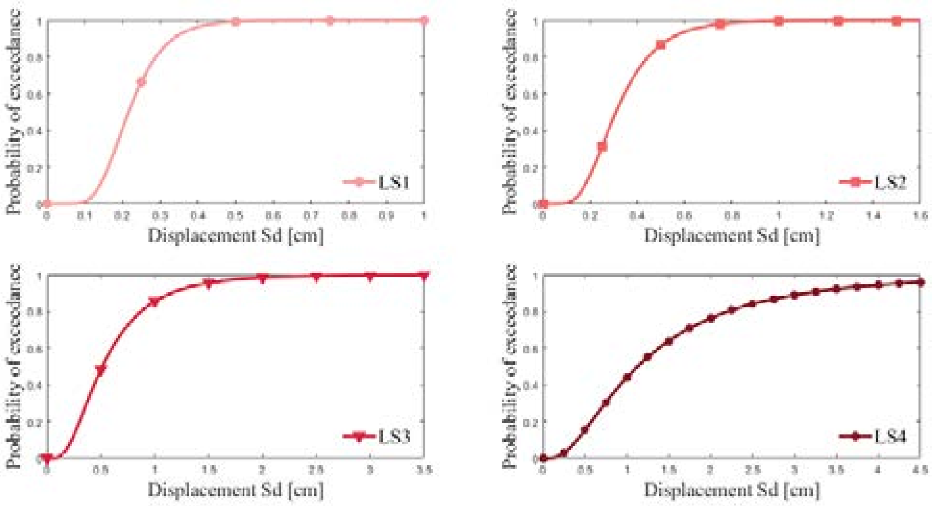

Fig. 4. Typological fragility numerical curves for different limit states.

4 COMPARATIVE ASSESSMENT OF THE FRAGILITY CURVES

Fragility functions estimate the probability of a structure to attain or exceed limit states of interest, depending upon a certain ground motion Intensity Measure. In seismic risk assessment, probabilities of exceedance of limit states of interest are useful to predict the seismic behavior of the built environment before an earthquake occurs.

The authors performed seismic fragility assessment for the class of the ordinary masonry buildings based on the empirical and numerical probabilities of exceedance.

Furthermore, the large portfolio of the gathered information and data allows to estimate the real damage scenario occurred after the 2016 earthquake. The suffered damage of each building of the stock was correlated to the Intensity Measure experienced by the attenuation law proposed by Crespellani [26], see Eq. 4, to prove the reliability of the proposed empirical method in predicting seismic damage scenario:

$$I_{EMS-98} = 6.39 + 1.756M_W - 2.747\ln(R + 7) \quad (4)$$

Where M_W is the moment magnitude occurred, set equal 6.2, and R is the distance from the epicenter, equal to 21.5 km. The discrete damage distributions for each buildings of the sample, evaluated for an intensity measure equal to 8.07, is reported in Fig. 5.

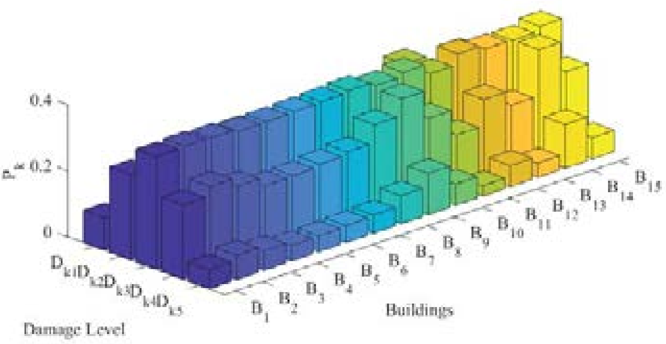

Fig. 5. Discrete damage distributions for I=8.07.

The percentage of buildings of the sample with a damage grade D_{k2} was equal to 6.67; with a damage grade D_{k3} was equal to 86.67, and with a damage grade D_{k4} equal to 6.67.

The forecast damage shows a good agreement with the real suffered damage: the preponderant level of damage is D_{k3}, with a discrepancy equal to 6.97 % with the real damage.

Moreover, the correlation law neglects the influence of possible site effects on damage scenario.

The results discussed above prove the capability and reliability of the empirical method to forecast the expected damage of buildings' sample.

Whereupon a comparison in terms of typological fragility curves is performed to compare empirical and mechanics-based methods, see Fig. 6, expressed in terms of a_g.

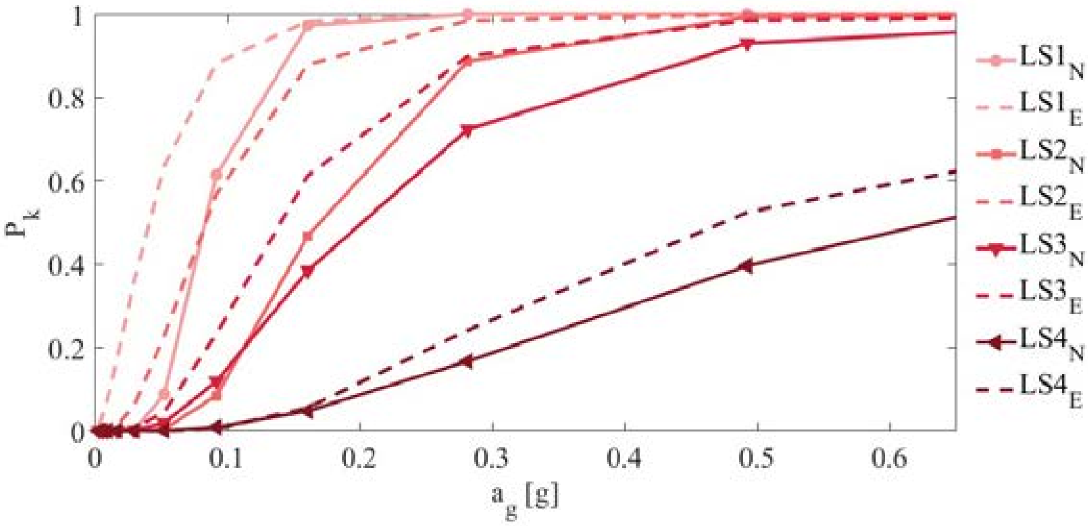

Fig. 6. Fragility curves comparison.

For a seismic demand encloses in the range 0-0.3 g, the discrepancy in terms of probability of exceedance for the LS1 reaches the value of 29.9 %; for the LS2 reaches the value of 47 %.

The comparison highlights a difference of fragility curves, more remarkable for the LS1 and LS2. Whereas the fragility curves referred to the attainment of the LS3 and LS4 shows a better agreement. For a seismic demand higher than 0.3 g, the discrepancy in terms of probability of exceedance for the LS3 reaches the value of 19 %; for the LS4 reaches the value of 25 %.

The empirical and numerical probability values of exceeding the limit state LS1 and LS2 may be regarded as too scattered to consider equivalently the two approaches.

Overall, the empirical curves overestimate the probabilities of the collapse, on the safe side in predicting the damage scenario.

5 CONCLUSIONS

The paper aims to derive fragility curves for masonry buildings' class, composed of fifteen selected buildings typical of the inner Central Italy, by empirical and numerical method. A simplified assessment of the seismic behavior of the buildings is performed, through an empirical method proposed by the authors, to provide a mean vulnerability index representative of the buildings' sample. Based on the empirical results, the mean damage was evaluated, according to the Macro Seismic Methodology to derive empirical fragility curves of the buildings' class. After that, fragility curves are derived from the results of non-linear static analysis. Based on a comparison between the different methodologies, the typological fragility curves show

different values of the expected damage, more scattered for the limit states LS1 and LS2. For a seismic demand encloses in the range 0-0.3 g, the discrepancy in terms of probability of exceedance for the LS1 reaches the value of 29.9 %; for the LS2 reaches the value of 47 %. Whereas the fragility curves referred to the attainment of the LS3 and LS4 shows a better agreement. For a seismic demand higher than 0.3 g, the discrepancy in terms of probability of exceedance for the LS3 reaches the value of 19 %; for the LS4 reaches the value of 25 %.
Thus, the current research results show that a typological approach fails for the LS1 and LS2 states of interest.
To improve the numerical fragility assessment of the buildings' typology, an investigation of the yielding displacements may be useful to propose an appropriate definition of the threshold for the slight and moderate damage states. The identification of suitable limit states for masonry buildings is still an open issue.
Similarly, to improve the empirical fragility assessment, the ductile factor of the masonry structures, set equal to 2.3 in the empirical formulation of the expected mean damage, could be deepened: even within the ordinary masonry class, buildings exhibit different ductile behaviour factors, showing the dispersion of the ductile parameter Q.

Therefore, the empirical typological fragility assessment ensures accurate and quick seismic vulnerability prediction on large scale, reducing computation time of seismic analysis of buildings' class. For the LS1 and LS2 limit states, the current research points out that a typological approach requires more accurate quantitative parameters to grasp the buildings' seismic behavior, with either approaches. To improve the fragility assessment of the buildings' typological class, an investigation of the onset of the damage may be useful to propose an appropriate definition of the threshold for the slight and moderate damage states. Thus, the limitations of each approach in forecasting damage scenarios and supporting resilience-enhancing strategies could be removed improving observational, experimental and numerical data to better deepen the seismic behavior of buildings under investigation.

6 ACKNOWLEDGMENTS

The authors would like to thank S.T.A. DATA company for providing the academic license of the 3Muri software.

REFERENCES

[1] A. Aloisio, R. Alaggio, M. Fragiacomo, Fragility functions and behavior factors estimation of multy ì-story cross-laminated timber structures characterized by an energy-dependent hysteretic model. *Earthquake Spectra,* **37 (1)**, https://doi.org/10.1177/8755293020936696.

[2] A. Mouyiannou, M. Rota, A. Penna, G. Magenes, Identification of Suitable Limit States from Nonlinear Dynamic Analyses of Masonry Structures. *Journal of Earthquake Engineering*, **18 (2)**, 231-263, 2014.

[3] M. Rota, A. Penna, G. Magenes, A methodology for deriving analytical fragility curves for masonry buildings based on stochastic nonlinear analyses. *Engineering Structures*, **32**, 1312-1323, 2010.

[4] I. Ioannou, T. Rossetto, D. Grant, Use of regression analysis for the construction of empirical fragility curves. *15th World Conference on Earthquake Engineering (15 WCEE),* Lisboa, Portugal, 2012.

[5] A. Miano, F. Jalayer, G. Forte, A. Santo, Empirical fragility assessment using conditional GMPE-based ground shaking fieldJ.s: application to damage data for 2016 Amatrice Earthquake. *Bulletin of Earthquake Engineering*, **18,** 6629-6659, 2020.

[6] C. Del Gaudio, G. De Martino, M. Di Ludovico. G. Manfredi, A. Prota, P. Ricci, G. Verderame, Empirical fragility curves for masonry buildings after the 2009 L'Aquila, Italy, earthquake. *Bulletin of Earthquake Engineering*, **17,** 6301-6330, 2019.

[7] J. Park, P. Towashiraporn, J.I. Craig, B. J. Goodno, Seismic fragility analysis of low-rise unreinforced masonry structures. *Engineering Structures*, **31,** 125-137, 2009.

[8] S. Saloustros, L. Pelà, F.R. Contrafatto, P. Roca, I. Petromichelakis, Analytical derivation of seismic fragility curves for historical masonry structures based on stochastic analysis of uncertain material parameters. *International Journal of Architectural Heritage*, **13 (7)**, 1142-1164, 2019.

[9] M. Rota, A. Penna, G. Magenes, A procedure for deriving analytical fragility curves for deriving analytical fragility curves for masonry buildings. *14th World Conference on Earthquake Engineering, 14 WCEE,* Beijing, China, 12-17 October 2008.

[10] A. Mouyiannou, M. Rota, A.Penna, G. Magenes, Indentification of Suitable Limit States from Nonlinear Dynamic Analyses of Masonry Structures. *Journal of Earthquake Engineering,* **18 (2)**, 231-263, 2014.

[11] M. Vettore, M. Donà, P. Carpanese, V. Follador, F. da Porto, M.R. Valluzzi, A multilevel procedure at urban scale to assess the vulnerability and the exposure of residential masonry buildings: the case study of Pordenone, Northeast Italy. *Heritage,* **3**, 1433-1468, 2020.

[12] N. Chieffo, F. Clementi, A. Formisano, S. Lenci, Comparative fragility methods for seismic assessment of masonry buildings located in Muccia (Italy). *Journal of Building Engineering*, **25,** 2019.

[13] A. Simoes, J. Milosevic, H, Meireles, R. Bento, S. Cattari, S. Lagomarsino, Fragility curves for old masonry buildings types in Lisbon. *Bulletin of Earthquake Engineering*, **13,** 3083-3105, 2015.

[14] I. Capanna, A. Aloisio, F. Di Fabio, M. Fragiacomo, Sensitivity Assessment of the Seismic Response of a Masonry Palace via Non-Linear Static Analysis: A case Study in L'Aquila (Italy). *Infrastructures*, **6(1),** 8, 2021.

[15] A. Formisano, Theoretical and numerical seismic analysis of masonry buildings aggregates: Case Studies in San Pio Delle Camere (L'Aquila, Italy). *Journal of Earthquake Engineering*, **21,** 227-245, 2017.

[16] G. Grunthal, European Macroseismic Scale *1998 (EMS-98). European Seismological Commission on Engineering Seismology*. Sub commission on Engineering Seismlogy, Working Group Macro Seismic Scales 15:101.

[17] F. Galadini, E. Falcucci, S. Gori, P. Zimmaro, D. Cheloni, J.P. Stewart, Active faulting in source region of 2016-2017 Central Italy event sequence. *Earthquake Spectra*, **34**, 1557-1583, 2018

[18] G. Brando, G. De Matteis, E. Spacone, Predictive model for the seismic vulnerability assessment of small historic centres: Application to the inner Abruzzi Region in Italy. *Engineering Structure*, **153**, 81-96, 2017.

[19] A. Formisano, G. Florio, R Landolfo, FM. Mazzolani, Numerical calibration of an easy method for seismic behaviour assessment on large scale of masonry building aggregates. *Advances in Engineering Software*, **80**, 116-138, 2015.

[20] S. Lagomarsino, S. Giovinazzi, Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. *Bulletin of Earthquake Engineering*, **4,** 415-443, 2006.

[21] J.R. Murphy, L.J. O'Brien, The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters. *Bulletin of the Seismological of America,* **67 (3)**, 877-915, 1977.

[22] S.T.A. DATA 3MURI (2009) Seismic calculation of masonry structures according to M.D. 14/01/2008. New technical codes for constructions.

[23] Ministerial Decree of Public Works, *Updating of Technical codes for constructions, M.D. 17/01/2018*. Official Gazette of the Italian Republic n.42, 20 February 2018.

[24] Ministerial Decree of Public Works, *Instructions for the application of the updating "Technical codes for construction, M.D. 17/01/2018*. Official Gazette of the Italian Republic n.42, 20 February 2018.

[25] A.K. Chopra, R.K. Goel, Capacity-demand-diagram methods based on inelastic design spectrum. *Earthquake Spectra,* **15**, 637-656.

[26] T. Crespellani, C.A. Garzonio, Seismic risk assessment for the preservation of historical buildings in the city of Gubbio, Geotecnical Engineering for the Preservation of Monuments and Historical Sites. *International Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic Sites,* Napoli, Italy, 3-4 October, 1996.