The risk assessment of the Vallicelle district located in Camerino

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ABSTRACT
This paper applies the Performance-Base Earthquake Engineering (PBEE) framework to estimate the risk of a urban district recently hit by an earthquake, in order to compare model prediction with effective damage observed after the event.
For this purpose, the reinforced concrete buildings of the Vallicelle district of Camerino, are considered. This district consists of different typologies of structures (Low, Middle and High rise) built at different times conforming to different seismic codes. After the "Central Italy 2016" earthquake, a detailed survey of damage was carried out, as well as studies about the seismic hazard of this area, subjected to seismic wave amplification.
In the PBEE framework, the seismic response of the structures is described by means of fragility curves proposed in literature according with the typologies of buildings present in the area and a loss analysis in terms of expected annual losses is carried out. Finally, a comparison with the observed damage experienced after the seismic sequence is provided.
This work is a summary of the paper published within COMPDYN 2019 (Canuti et al., 2019).

1 INTRODUCTION

A proper quantification of the losses plays an important role to develop resilient and sustainable communities especially in areas hit by frequent seismic sequences. Prediction of potential economic losses and, more generally, consequences due to hazardous events, is a key point for prevention planning and emergency organization. To this aim, it is necessary to define reliable models for event predictions, building response and consequences evaluation.

The Performance Based Engineering framework (PBEE) presented by the Pacific Earthquake Engineering (PEER) is a robust methodology to evaluate the structural performance in a rigorous probabilistic manner without relying on expert opinion, considering the uncertainty in the seismic hazard, structural response, potential damage and economic losses.

The PBEE involves four different stages: hazard analysis, structural analysis, damage analysis and loss analysis (Cornell and Krawinkler 2000, Deierlein et al., 2003) in order to quantify the decision variables. These latter identify the seismic performance assessment in terms of direct interests of various stakeholders such as fatalities, economic losses and downtimes (Porter 2003). A complete methodology of loss estimation is presented in Hazus (FEMA. HAZUS99) and Risk-UE (Milutinovic and Trendafiloski, 2003) as well, where all the aspects of the PBEE framework are investigated (Whitman et al., 1997, Kircher et al. 1997, Kircher et al., 1997).

This paper analyses the capacity of the PBEE framework to estimate the expected losses at level of urban district. For this purpose, the Reinforced Concrete (RC) buildings of the Vallicelle district of Camerino are considered. This district is composed by different typologies of RC structure (Low, Middle and High-rise) built at different times designed considering the seismic actions provided by early versions of seismic Italian code. Furthermore, the area of Vallicelle district experienced the seismic sequence of Central Italy 2016, which includes many events with similar magnitude. The sequence started from August 24th with an event of magnitude Mw= 6.1 followed by other two events characterised by Mw= 5.9 and Mw= 6.5 in October 26th and 30th (Sextos et al., 2018), respectively. After these seismic events, most of structures of the district exhibit different level of damage.

The seismic behavior of the structures, necessary to perform the PBEE framework, is defined starting from the fragility curves available in literature. In particular the Syner-G documents (Pitilakis et al., 2014, Pitilakis et al., 2014) provides groups of fragility curves for different typologies classified on the type of structure (masonry and reinforced concrete), the height of buildings (three classes depending on the number of floors), the design level of seismic load (High-Code, Moderate-Code, Low-Code, Pre-Code) and the use of the constructions (residential, commercial etc.).

The seismic hazard of the area is evaluated based on the Italian standard definition, providing the expected Peak Ground Acceleration (PGA) in terms of the mean annual frequency of exceedance rate λ. In addition, specific studies on the seismic wave amplification phenomena due to the geological and geotechnical local site condition have bees recently developed and they are considered in the analysis.

Losses are evaluated in terms of Expected Annual Loss [EAL] considering the replacement costs available in the Hazus documents (HAZUS®MH Technical Manual , 2003). Furthermore, the registered damage after seismic sequence of Central Italy 2016 is finally compared with the EAL furnished by the PBEE framework.

2 DESCRIPTION OF THE SEISMIC SEQUENCE OF CENTRAL ITALY 2016

The first mainshock of the seismic sequence that struck Central Italy Regions occurred on August 24th of 2016; this event generated about 300 causalities and important damages to buildings with great economic losses. This mainshock was characterised by a magnitude Mw=6.1 with epicenter at 1 km W of Accumoli, and the Peak Ground Accelerations (PGAs) recorded nearby the epicenter was about 0.45g. After this mainshock other two events characterised by Mw=5.9 and Mw=6.5 in October 26th and 30th were occurred in the Region; these last events were characterised by a location of the epicenter 3 km S away from Visso and 4 km NE from Norcia respectively. During the last mainshock, the maximum PGA recorded nearby the epicenter was about 0.48g. The area was interested by about 6500 aftershocks with magnitude Mw ranging from 2.3 to 5.5, occurred between August 2016 and January 2017. Figure 1 shows the locations of the mainshock epicenters superimposed to the envelope of shake maps in terms of PGA of main events. The shake map has been obtained by post processing the shake data provided by the Italian National Institute of Geophysics and Volcanology (INGV. Shake maps data) through the QGIS open source GIS software (QGIS Development Team 2015). The value of PGA processed by INGV is referred to the stiff soil characterised by shear wave velocity higher than 800 m/s and it is estimated by means of empirical attenuation laws starting from the shaking recorded in the accelerometric stations distributed along the territory. It should be emphasized that the PGA estimated by INGV do not consider the possibility of the local shaking amplification due to the geological condition.

Table 1 reports the values of the PGA estimated in the Vallicelle district by means the INGV data processing after the mainshocks; the event of 30 October produced a maximum value of PGA in the area.

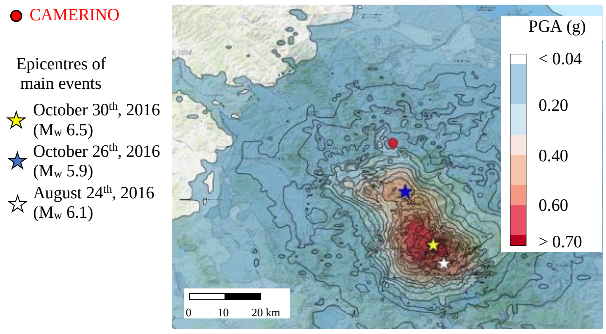


Figure 1: Envelope of maximum PGA registered after the three mainshocks of the 2016 seismic sequence.

Table 1: Estimated PGA in Vallicelle district after the mainshocks.

Event	Estimated PGA
August 24th, 2016	0.055g
October 26th, 2016	0.126g
October 30th, 2016	0.168g

3 VALLICELLE DISTRICT

Camerino is a Municipality of the Marche Region (Central Italy) and Vallicelle is one of the most populated district of the small town of Camerino and it is located on the southern area near the historical center (Figure 2). This district mainly consists of residential buildings, including some commercial activities.

The area was built mainly after the 1980, and the most recent buildings were risen few years ago. This area experienced a higher level of damage after the seismic sequence of 2016, due to the proximity of the second and third mainshock (October 26th and 30th) epicenters and due to the geology of the area.

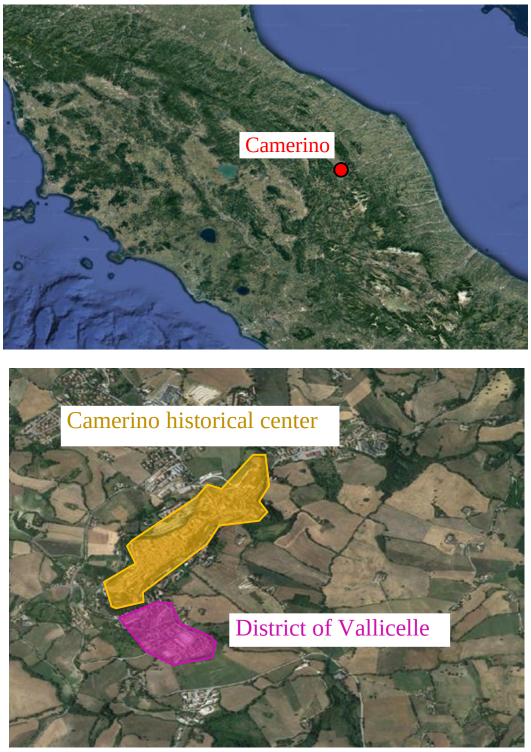


Figure 2: Location of Camerino city and Vallicelle district.

3.1 Buildings General Information

Most of buildings of Vallicelle district are made by Reinforce Concrete (RC) structures designed according to early versions of the seismic Italian design code, which defines the seismic structural response by linear static analysis, without considering the damage control at low intensities and specific checks in terms of ductile and fragile mechanisms provided in the last version of code. In addition, the possible amplification of the seismic input due to the local site effect was considered in a simplified and inadequate manner.

In order to evaluate the seismic response of buildings in the context of a district-oriented risk assessment, it is necessary to classify the structures into typologies collecting buildings with similar structural behavior. Consistently with the level of the building knowledge, the subdivision in typologies based on the number of floors, represents a satisfactory approach. Based on this strategy, it is possible to group the RC buildings in three classes: Low Rise (LR) characterised by 1-3 floors, Middle Rise MR by 4-7 floors and Hight Rise (HR) constituted by 8-19 floors. Moreover, it is possible to associate the range of possible first elastic periods of vibration T_1 to each typologies of buildings. In particular, the range [0.1s, 0.5s] can be associated to LR structures, the range [0.4s, 0.8s] to MR structures and the range [0.7s, 1.1s] to HR structures. Figure 3 shows the distribution over the Vallicelle district the building typology; in particular 27 buildings fall in the LR typology, 21 buildings in MR typology and only one building falls in HR typology.

4 SEISMIC RISK ASSESSMENT

Analytical loss estimation can be determined by following a direct method, where the annual rate of exceedance of a loss value is determined by considering all the uncertainties in a unitary way and by assuming probabilistic models for all of them (Scozzese et al., 2019, Bradley et al., 2009). As an alternative approach, the problem can be separated in blocks, as proposed in the PEER frameworks (Porter, 2003, Günay and Mosalam, 2013), by exploiting some advantages coming from the conditional evaluation of rare events (Scozzese et al., 2019). In the following, the latter approach has been considered, by determining the annual rate of exceedance of costs by the equation:

$$\lambda_C(c) = \iint G_C(c\,|\,d)\, f_D(d\,|\,i)\, dd \left|\lambda_I^{'}(i)\right| di \qquad (1)$$

In this study, “loss” is referring to the random variable C providing the cost required to repair/replace the facilities after an earthquake, the random variable D describes the building damage and I is a random variable measuring the ground motion intensity. Notation $G_X(x)$ indicates the complementary distribution function of the argument x, and $f_X(x) = -G_X^{'}(x)$ denotes the related probability density function and apex denotes derivative.

Figure 3: Buildings typology distribution of Vallicelle district.

In the following, the results are presented and discussed with reference to the EAL per year, provided by the integral:

$$EAL = \int c\left|\lambda_C^{'}(c)\right| dc \tag{2}$$

4.1 *Seismic Hazard Assessment*

Taking into account the potential seismogenic sources, Italian standard (Ordinanza PCM 3519) defines the seismic hazard over the territory, providing the expected PGA for a discrete number of mean annual frequency of exceedance rate λ in the interval between 0.004 - 0.033.

Generally, the relationship between annual rate of exceedance and ground-motion intensity is well fitted by a power law expression (Cornell et al., 2002, Kennedy, 1999), and it is possible to define a closed form expression providing a reasonable estimation of the hazard

$$\lambda_I(i) = k_0(i)^{-k} \tag{3}$$

where k_0 and k are empirical constants. In this study, the seismic intensity i is measured by PGA and the parameters of the power law expression are estimated considering two earthquake intensity levels corresponding to 63% and 5% probabilities of exceedance in 50 years. The former is associated to $\lambda = 0.02$ and it is suggested for checks related to the Damage Limit State (DLS) and the latter is associated to $\lambda = 0.001$ and it is suggested for checks related to Collapse Limit State (CLS). Adopting this strategy, k and k_0 assume the values -2.726 and 2.257E^{-5} respectively. Figure 4 shows the hazard curve adopted in the analysis.

In addition, in the evaluation of the seismic hazard, the local amplification phenomena due to the geological and geotechnical local site condition are considered. The Vallicelle area is characterised by a large wave amplification caused by local site effects. Studies of Seismic Microzonation (SM), performed by the Italian Center of Microzonation (Maccari, 2017), provide a general overview of the spatial distribution of amplification factors (Figure 5a). These effects were evaluated considering three ranges of periods for the superstructure, [0.1s, 0.5s], [0.4s, 0.8s], [0.7s, 1.1s], providing for each range the corresponding Amplification Factor (FA). These ranges of period are coherent with the buildings typologies mentioned above (LR, MR and HR). The SM of Vallicelle district identifies two sub areas characterised by a high (Area 1) and low (Area 2 and Area 3) amplification effect. Figure 5b reports for each range of period the relevant FA. In particular, Area 1 is characterised by FA between 1.5 (LR buildings) and 2.8 (for MR buildings), while for the Area 2 and Area 3 the maximum value of FA is 1.4 (LR buildings).

Figure 6 illustrates the extrapolated seismic hazard of Camerino according to the Equation (3) (red line) with respect to the hazard evaluation derived considering the site amplifications effects (blue line).

Finally, Table 2 reports for each building the relative area of amplification considered in the following analyses.

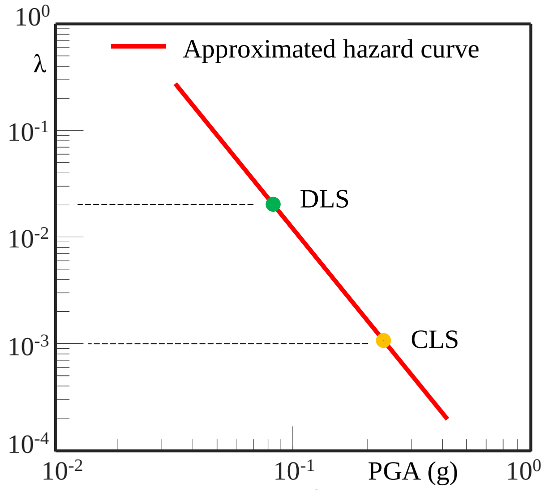


Figure 4: Exceedance rates for seismic hazard intensity parameter at bedrock site.

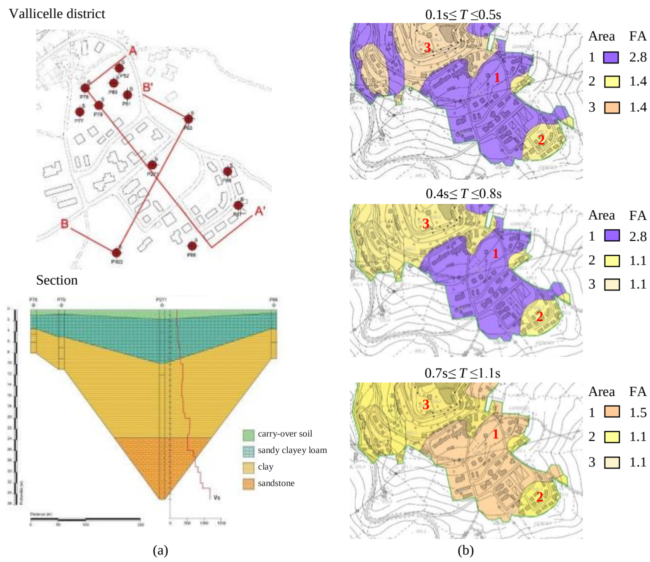


Figure 5: Vallicelle geology: (a) soil stratigraphy and (b) FA for each homogeneous sub-area.

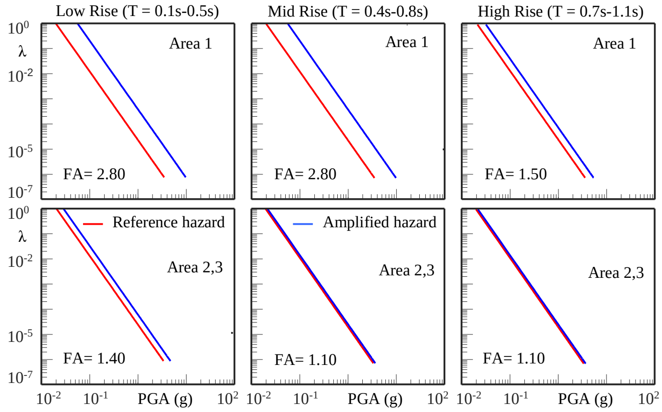


Figure 6: Seismic hazard considering the site effect amplification.

Table 2: Buildings grouped by amplification area.

Buildings	Amplification Area
A, B, C, D, E, F, G, H, I, L, M and O	Area 1
N	Area 2
K, and J	Area 3

4.2 *Loss Estimation*

The loss estimation can be evaluated by damage functions $G_C(c|d)$, which described the probability of exceedance of the loss value c, given the damage level d. Generally, the damage level is described by a discrete variable; in this case d_k ($k=0,1,..,N_D$) denotes the damage level within a finite number N_D+1 of ordered possible damage states and the functions $G_D(d_k|i)$ ($k=0,1,..,N_D-1$) describe the probability that the damage state is larger than d_k, given the seismic intensity i. The most common way to define earthquake consequences is a classification based on qualitative approach (0 = no damage; 1 = slight/negligible; 2 = moderate; 3 = heavy; 4 = very heavy, 5 = destruction) (Grünthal, 1998), which requires a description of each damage state.

The fragility curves are often efficiently approximated by a closed form expression based on a lognormal probability distribution function:

$$G_D(d_k|i)=\Phi\left[\frac{\ln(i)-\mu_k}{\beta_k}\right] \quad (4)$$

where, i is the intensity measure expressed in PGA and μ_k and β_k are the parameters associated with the response of the structure.

The probability $f_D(d_k|i)$ of structure being in the k-th damage state given intensity i, derives from previous equation (4) and can be evaluated by:

$$f_D(d_k|i)=\begin{cases}1-G_D(d_0|i) & k=0\\ G_D(d_k|i)-G_D(d_{k-1}|i) & k=1,2,..,N_D-1\\ G_D(d_{N_D-1}|i) & k=N_D\end{cases} \quad (5)$$

The Syner-G documents (Pitilakis et al., 2014 , Pitilakis et al., 2014) collected an inventory of fragility functions grouping the structures in classes, characterised by a similar response to earthquake (with respect to material, geometry, design code level). In particular, the classification of the buildings are made considering the type of structure (masonry and reinforced concrete) height of buildings (three classes depending on the number of floors), the design level of seismic load (High-Code, Moderate-Code, Low-Code, Pre-Code) and the use of the constructions (residential, commercial etc.).

In this work, three classes of RC buildings have been considered, Low Rise (LR), Mid Rise (MR) and High Rise (HR) respectively, designed for a moderate intensity earthquake (PGA = 0.1-0.3g). Furthermore, three level of damage state d_k (with $k=0,1,2$) has been considered and connected with a particular Limit State of the structure provided by the Italian standard code, which provides the boundary between two different damage conditions defining a damage thresholds. In particular, the structure is considered damaged with level d_0 (undamaged), if the LS of DLS has not been reached, the structure is damaged with level d_2 if the LS of CLS is exceeded. Finally, the structure is damaged with level d_1 if only the DLS is exceeded. Figure 7 reports the fragility curves adopted for each class of structure assuming the parameter of curve μ_k and β_k collected in Table 3 (Pitilakis et al., 2014) and describing the mean values of parameters relevant to fragility curves observed within each class.

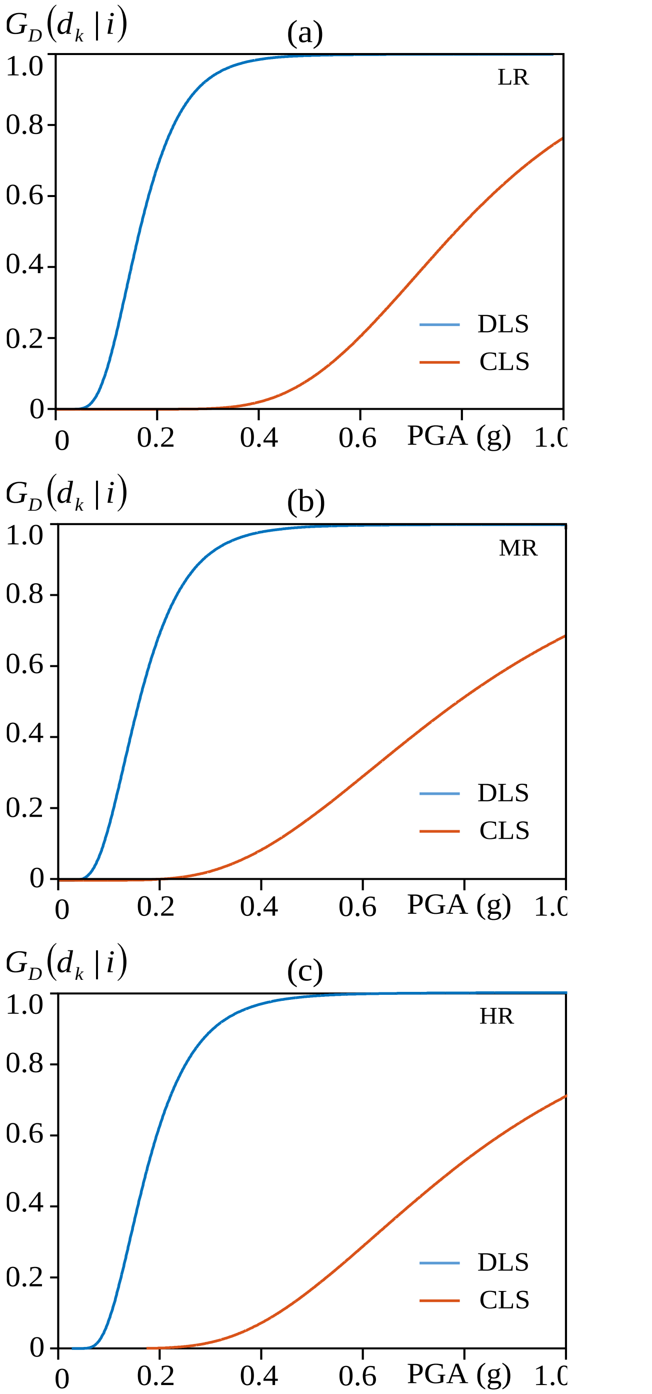


Figure 7: Fragility curves adopted in the analyses: (a) LR buildings; (b) MR buildings and (c) HR buildings.

Table 3: Parameters adopted in the analyses

LR			
DLS	CLS	DLS	CLS
μk(g)	βk	μk(g)	βk
0.16	0.43	0.84	0.26
MR			
DLS	CLS	DLS	CLS
μk(g)	βk	μk(g)	βk
0.16	0.43	0.77	0.46

HR			
DLS	CLS	DLS	CLS
μk(g)	βk	μk(g)	βk
0.16	0.43	0.78	0.46

With respect to the set of damage states previously discussed and referred to EMS98 [23], in the reduced set used here the damage state d_0 include both the case of no damage and slight/minor damage, the damage state d_1 include both moderate and heavy damage and the damage state d_2 concerns heavy damage and collapse.

The economic implication of damage state is specified in terms of loss ratio c defined as ratio between repair costs and the total replacement cost rc (value of the facility), and $G_C(c \mid d_k)$ represents the probability of exceedance of the cost connected to the level of damage d_k. Based on the Hazus study (HAZUS®MH Technical Manual , 2003), a deterministic relation is assumed between damage level and costs. The values c_0 =1%, c_1=26%, and c_2=100% have been associated to the damage states d_0, d_1, and d_2 respectively, and $G_C(c \mid d_k)$ can be reduced to the Heaviside function $H(c - c_k \mid d_k)$. Thus, the Equation (1) assumes the simplified form:

$$\lambda_C(c) = \sum_k \int H(c - c_k \mid d_k)\, f_D(d_k \mid i) \left|\lambda_I^{'}(i)\right| di \tag{6}$$

where f_D varies class by class of structures and λ_I varies according to the shake local amplification phenomena of the site.

5 RESULTS

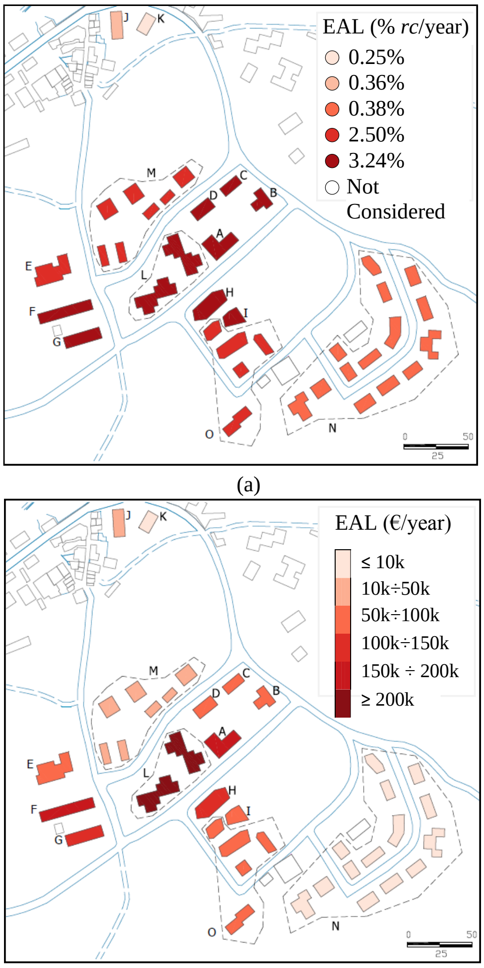
In this chapter, results of the seismic risk assessment of Vallicelle district, reported in Figure 8, are presented and commented.

Figure 8a reports the distribution of the EAL over Vallicelle district, measured by the ratio between the repair costs and the replacement costs. The values of EAL observed in buildings located in Area 1 are generally larger than EAL of buildings in Area 3 and 2, despite different typologies are present in both the areas. Therefore, in this case study, the FA is the main parameter influencing EAL.

In Area 1 the EAL values vary from 2.50% to 3.24% and the highest values regards the MR typology. In Area 2 the EAL value is 0.38% due to the presence of only one class of buildings.

Finally, Area 3 shows the lowest values of EAL, varying from 0.25% to 0.36%

Figure 8b reports the distribution of the EAL over Vallicelle district in terms of total repair cost per year. The total replacement cost *rc* is evaluated considering a unitary cost 1500 €/m^2 (Asprone et al., 2013) multiplied by the area and the number of floors of each facility. The maximum value of EAL (212k €/year) is obtained for the building group *L*, while the value of 4.7k €/year is related to the building group *N* and *K* due to their low risk area.



(a)

(b)

Figure 8: Estimated EAL expressed as: (a) percentage of replacement costs; (b) total replacement costs.

6 OBSERVED DAMAGE AFTER THE SEISMIC SEQUENCE 2016

This section reports the damage suffered by the buildings after the Central Italy seismic sequence of 2016 and compares this with the expected damage evaluated starting from the fragility curves adopted in the analysis. The damage assessment is based on visual inspections (Di Ludovico et al., 2017), and it is classified following the EMS98 scale (Grünthal , 1998), considering six levels of damage (D0-D5). In details, Table 4 reports for each damage level the classification of the RC buildings damage according with the observational approach adopted as follow.

Table 4: Classification of damage to buildings of reinforced concrete.

Damage Level	Description
D0	No damage
D1	Negligible damage (no structural damage, slight non-structural damage)
D2	Moderate damage (slight structural damage, moderate non-structural damage)
D3	Substantial to heavy damage (moderate structural damage, heavy non-structural damage)
D4	Very heavy damage (heavy structural damage, very heavy non-structural damage)
D5	Destruction (very heavy structural damage)

Figure 9 shows the damage distribution recorded in the Vallicelle district; it can be observed that the main damages were registered in the buildings A-F falling in the Area 1 characterised by a higher values of FA according to the MS study. In particular the building B suffered a serious structural damage (D4) probably due to the irregularity in the structural and non-structural systems (pilotis floor, ribbon window at the ground floor, eccentric staircase). However, the building groups L, and M are fully operative, while a level damage D1 was registered in the buildings E and G. Finally, the buildings J and K falling in the Area 3 experienced a level of damage D2 and D1 respectively, while all the buildings in the Area 2 are fully operative.

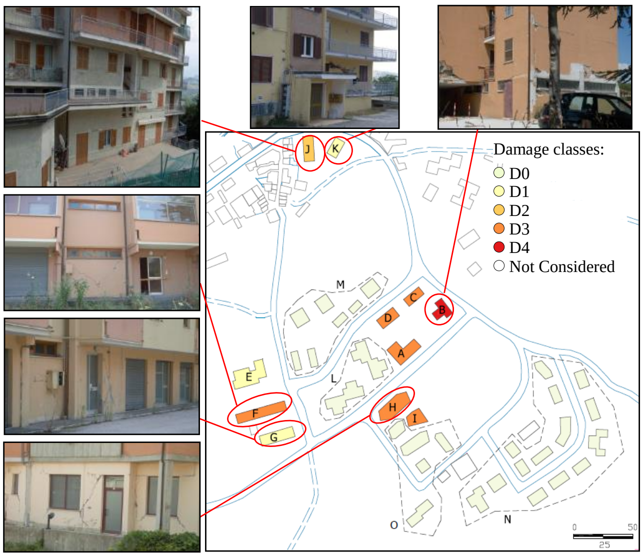


Figure 9: Observed damage after the Central Italy 2016 seismic sequence

The expected damage scenario is evaluated with reference to the October 30th event characterised by a magnitude M_W of 6.5 and epicentral distance relevant to Vallicelle district of about 30 km. The estimated PGA for the considered event, over the rigid soil (soil type A) in the area is $i_{\max}$ = 0.168g. The frequency distributions of expected damage state, conditioned by the event with intensity $i_{\max}$, is described by the discrete function $f_D\left(d_k \mid i_{\max}\right)$ introduced in Equation 5. According to reduced set of damage state previously introduced and discussed, the damage d_0 is related to damages D0-D1, the damage state d_1 is related to damages D2-D3, and d_2 is related to damages D4-D5 expected by the EMS98 scale.

Table 5 and 6 report the frequency distributions of the expected damage after the event of October 30th for the building following in the Area 1 and Area 2 and 3.Figure 10 reports the distribution of probability of damage over the Vallicelle district. The damage level d_1 (equivalent to D2-D3 in EMS98 scale) results to be the most probable damage with a probability greater than 67 % in all cases. The major probability of having a damage level d_2 (D4-D5 in EMS98) is expected for the MR building falling in the Area 1 and it is in agree with the registered damage. Indeed the greatest damage is registered in the Area 1 for the buildings A, D, C, F, H, and I. Moreover, it can be observed that the distribution of relative frequency is quite dispersed in many cases and this justifies the deviation from predicted damage mode and observed damage.

Table 5: Frequency distribution of damage for the buildings fallen in Area 1 after the event of October 30th.

	$f_D\left(d_0 \mid i_{\max}\right)$	$f_D\left(d_1 \mid i_{\max}\right)$	$f_D\left(d_2 \mid i_{\max}\right)$	Building groups
LR	0.49%	93.44%	6.08%	M, E, O
MR	0.81%	84.14%	15.05%	A,B,C,D ,F,G,H,I
HR	14.03%	84.85%	1.12%	-

Table 6: Frequency distribution of damage for the buildings fallen in Area 2 and 3 after the event of October 30th.

	$f_D\left(d_0 \mid i_{\max}\right)$	$f_D\left(d_1 \mid i_{\max}\right)$	$f_D\left(d_2 \mid i_{\max}\right)$	Building groups
LR	18.89%	81.10%	0.01%	N
MR	36.65%	63.18%	0.17%	K
HR	32.32%	67.52%	0.17%	J

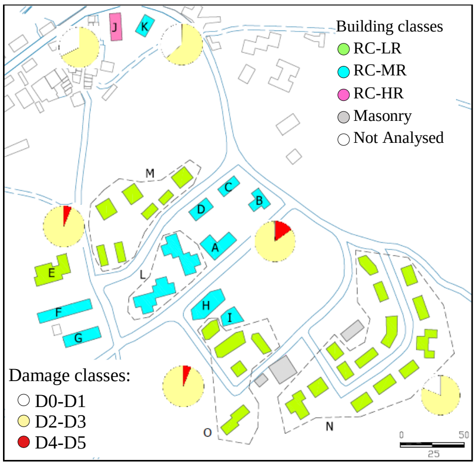


Figure 10: Distribution of damage probability of given by the October 30th event.

7 CONCLUSIONS

This paper applies the capacity of PBEE framework to evaluate the EAL at territorial scale. To this end, the RC buildings of Vallicelle district of Camerino struck by the seismic sequence of Central Italy 2016 are analysed, showing a diversified damage scenario. Various typologies of RC buildings characterise the district in accordance with specific criteria such as the height of the building (Low Rise, Mid Rise, High Rise), the code used for the seismic design, the construction period. Moreover, the seismic hazard is assessed considering the geological and geotechnical condition of the soil, useful for the evaluation of the shake amplification.

The structural response is defined based on the fragility curves proposed in Syner-G document and the loss analysis is outlined with EAL considering the replacement costs contained in the Hazus technical manual. Finally, a comparison with the observed damage is provided.

The main results of the study are the following:

- Considering the Area 1, buildings classified as MR have a largest value of EAL if compared with the LR that presented the same factor of shake amplification.
- Buildings fallen in Area 2 and 3 present lower values of EAL, in accordance with minor values of FA.
- The expected most probable damage evaluated for the event of October 30th is generally larger than the damage registered after the Central Italy seismic sequence.
- The most probable expected damage of Area 1 is in agreement with the experienced damage after the Central Italy seismic sequence of 2016, excepted for buildings L, M, and O that are undamaged.
- For Area 2 the experienced damage is the lower than the most probable, while for Area 3 the damage is in accordance with the observed one.
- The differences between the most probable damage and the observed damage are perhaps due to the large variability presents in the classes of fragility curves chosen from the literature and valid for groups of buildings with similar structural response.

REFERENCES

Canuti C., Dall’Asta A., Leoni G., Morici M., Risk assessment of Camerino municipality: a case study of Vallicelle district. 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, 2019

Cornell C.A., Krawinkler H, Progress and challenges in seismic performance assessment. PEER Center News 3, University of California, Berkeley, 2000.

Deierlein G.G., Krawinkler H.,Cornell C.A, A framework for performance-based earthquake engineering. 7th Pacific conference on earthquake engineering. Christchurch, New Zealand, 2003.

Porter K.A., An overview of PEER’s performance-based earthquake engineering methodology. 9th International conference on applications of statistics and probability in civil engineering. San Francisco, pp 973–980, 2003.

FEMA. HAZUS99 Technical Manual. Service Release 2. Washington (D.C., USA): Federal Emergency Management Agency, 2001.

Milutinovic Z.V., Trendafiloski G.S.. WP4 vulnerability of current buildings. Risk-UE Project: an advanced approach to earthquake risk scenarios with applications to different European towns, 2003.

Whitman R.V., Anagnos T., Kircher C.A., Lagorio H.J., Lawson R.S., Schneider P., Development of a national earthquake loss estimation methodology. Earthq Spectra, 13(4), 643–61, 1997.

Kircher C.A., Nassar A.A., Kustu O., Holmes W.T.. Development of building damage functions for earthquake loss estimation. Earthq Spectra, 13(4), 663–82, 1997.

Kircher C.A., Reitherman R.K., Whitman R.V., Arnold C, Estimation of earthquake losses to buildings. Earthq Spectra,13(4), 703–20, 1997.

Sextos A., Risi R., Pagliaroli A., Foti S., Passeri F., Ausilio E., Cairo R., Capatti M.C., Chiabrando F., Chiaradonna A., Dashti S., De Silva F., Dezi F., Durante M., Giallini S., Lanzo G., Sica S., Simonelli A.L., Zimmaro P., Local site effects and incremental damage of buildings during the 2016 Central Italy Earthquake sequence. Earthq Spectra, 34 (4), 1639-1669, (2018).

Pitilakis K., Crowley H., Kaynia A., SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk. Springer 2014.

Pitilakis K., Franchin P., Khazai B., Wenzel H., SYNER-G: Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline Systems and Critical Facilities. Springer 2014.

Multi-Hazard Loss Estimation Methodology. HAZUS®MH Technical Manual. National Institute of Building Sciences and Federal Emergency Management Agency, Washington, D.C., pp. 712, 2003.

INGV - Shake maps data are available http://shakemap.rm.ingv.it/shake/index.html

QGIS Development Team (2015). QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org.

Scozzese F., Dall'Asta A., Tubaldi E., Seismic risk sensitivity of structures equipped with anti-seismic devices with uncertain properties. Structural Safety, 77, 30-47, 2019.

Bradley B. A., Dhakal R., Cubrinovski M., MacRae G., Lee D., Seismic loss estimation for efficient decision making. Bulletin of the New Zealand Society for Earthquake Engineering, 42(2), 96-110, 2009.

Porter K.A., An overview of PEER’s performance-based earthquake engineering methodology. Proceed. of Ninth International Conference on Applications of Statistics and Probability in Engineering, San Francisco, California, 2003.

Günay S., Mosalam M. K.. PEER Performance-Based Earthquake Engineering Methodology, Revisited. Journal of Earthquake Engineering, 17(6), 829-858, 2013.

Ordinanza PCM 3519 del 28/04/2006, in Italian.

Cornell C.A., Jalayer F., Hamburger R.O., Foutch D.A., Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines. Journal Struct Eng, 128(4), 526–33, 2002.

Kennedy R.P., Risk based seismic design criteria. Nucl Eng Des, 192(2–3), 117–35, 1999.

Maccari M.. Relazione illustrativa per la microzonazione di terzo livello (Comune di Camerino) in Italian, 2017.

Grünthal G., Cahiers du Centre Européen de Géodynamique et de Séismologie: Volume 15 – European Macroseismic Scale 1998. European Center for Geodynamics and Seismology, Luxembourg, 1998.

Asprone D., Fatemeh J., Simonelli S., Acconcia A., Prota A., Manfredi G., Seismic insurance model for the Italian

residential building stock. Structural Safety, 44, 70-79, 2013.
Di Ludovico M., Digrisolo A., Graziotti F., Moroni C., Belleri A., Caprili S., Carocci C., Dall'Asta A., De Martino G., De Santis S., Ferracuti B., Ferretti F., Fiorentino G., Mannella A., Marini A., Mazzotti C., Sandoli A., Santoro A., Silvestri S., Sorrentino L., Magenes G., Masi A., Dolce M., Prota A., Manfredi G. c) The contribution of ReLUIS to the usability assessment of school buildings following the 2016 central Italy earthquake. Bollettino di Geofisica Teorica ed Applicata, 58(4):353–376, 2017.