Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 3338-3359

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

SEISMIC ASSESSMENT OF MASONRY BUILDINGS AT TERRITORIAL SCALE

C. Iacovino[1], A. Flora[1], D. Cardone[1] and M. Vona[1]

[1] School of Engineering, University of Basilicata, Italy

Viale dell'Ateneo Lucano, 10

{chiara.iacovino, amedeo.flora, donatello.cardone, marco.vona}@unibas.it

Abstract

In the last decades, a number of methodologies for the performance based-loss assessment of buildings have been proposed and developed. Among those, the PEER Performance-Based Earthquake Engineering (PBEE) methodology represents the most comprehensive approach providing probabilistic estimates of seismic losses. However, those procedures are suitable for building-specific evaluations, appearing extremely time-consuming if applied at the urban scale. Recently, many authors proposed simplified approaches relating the economic losses to the structural response (i.e. Engineering Demand Parameters, EDP) derived from analysis methods within the reach of the most practicing engineers. Many of these procedures have been also implemented in current seismic codes. In this paper a seismic loss assessment of the residential masonry building stock of the city center of Potenza is performed based on the simplified approach currently adopted within the Italian Seismic Risk Classification. After a preliminary typological characterization of the investigated structures, the mentioned methodology has been applied to derive the expected annual loss of masonry buildings, deriving information on the seismic resilience of the examined built heritage at urban scale. Preliminary socio-economic considerations of seismic scenarios at urban scale are discussed. The results presented herein are part of a comprehensive research activity performed within PON-AIM 2014-2020 project aimed at the definition of the seismic resilience of the examined area.

Keywords: Masonry buildings, Seismic Risk Assessment, Vulnerability, Built Heritage.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8715.19404

1 INTRODUCTION

Observations from worldwide earthquakes illustrated the severe economic consequences in highly developed regions of society. In general, these economic consequences can be primarily attributed to: (i) direct economic losses associated with repairing damage within a structure [1], (ii) direct losses associated with injuries and casualties and (iii) indirect losses associated with the loss of income due to business disruption [2].

More in details, the economic losses from physical damage strongly influence the community's recovery capability, especially when a relevant portion of the building stock is represented by unreinforced masonry (URM) constructions. As a matter of fact, damage on masonry buildings usually involves expensive and time-consuming repairing activities that can be carried out only by expert builders, thus further enhancing the cost of the interventions. Moreover, the larger is the period of time requested to restore the operativity of the structure, the larger is the downtime, namely, the indirect losses associated with loss of productivity, business interruption and cost of occupants reallocation. All that considered, an appropriate loss estimation of buildings is crucial for the development of resilient communities in seismic prone areas [3], [4], providing risk-based information, which may help Governments, stakeholders and owners to define the priority of interventions or policies for disaster prevention.

In the last decade, several loss estimation methodologies have been proposed, although accurate quantification of loss is still a difficult task subject due to several uncertainties [5]-[8]. In recent years the accurate Performance Based Earthquake Engineering (PBEE) approach proposed by the US FEMA P-58 has been increasingly adopted for the seismic assessment of structures [9]. The method consists of a number steps implemented to provide information regarding the building' performances in terms of probability of exceedance (PoE) of specific Decision Variables (DV), such as monetary losses, causalities, downtime [10]. In the first step, a given site location and local characteristics are related to the seismic hazard expected from the surrounding region. In the second step, a probabilistic description of the seismic demand to the building at increasing levels of ground motion intensity is obtained from the results of a series of Nonlinear Response History Analyses (NRHAs). Subsequently, damage to individual structural and nonstructural components is estimated, through a suite of fragility curves, as a function of selected Engineering Demand Parameters (EDPs) (e.g., peak inter-story drifts, floor accelerations etc.) computed in the second step of analysis. Finally, expected losses are estimated through a set of suitable consequence functions, based on the level of damage sustained by each component.

The main output parameter of the PBEE approach is represented by the expected annual loss (EAL) [11], defined as the average economic loss expected to accrue every year in the structure, considering both the direct repair costs related to damage and the social costs associated to downtime. The synthetic information expressed by these parameters represents a powerful tool for the stakeholders. In particular, the EAL estimations in both the as-built and retrofitted configurations can be assumed as input parameters for a cost–benefit analysis, aimed at the rational choice of the optimal retrofit intervention among different options.

However the PBEE approach is still infrequently employed for the assessment of existing URM constructions. Difficulties in the application of the methodology arise in the calculation of the EAL involving the building's performance assessment at increasing intensity earthquakes. This requires significant computational efforts and is generally unaffordable for applications in the common practice.

Recently, simplified approaches, relating the economic losses to the structural response (engineering demand parameters, EDP) derived from analysis methods within the reach of the most practicing engineers, have been proposed [12], [13]. In particular, the main simplification lies in relating a given performance level (PL) to an expected economic loss calculated based on specific story-based loss function [14] or pre-defined based on the actual structural typology [15]. The latter approach has been recently implemented within the Italian Seismic Risk Classification [16] to evaluate the "seismic quality" of existing buildings, providing a specific score system articulated in eight seismic risk classes. Generally speaking, the mentioned procedure appears useful when the amount information regarding the building geometry and structural details is limited and a reliable characterization of the seismic performances is uncertain. The Italian Seismic Risk Classification defines eight seismic performance-based risk classes in terms of EAL and structural collapse capacity. Those classes are employed to give an overall rating on a letter-based scale from A+ to G, similar to the appliances energy consumption scale used in Europe [17].

In this paper, the seismic loss assessment of the residential masonry building stock of the city center of Potenza (southern Italy) is presented. First of all, a complete identification and typological characterization of the residential masonry structures has been performed. Subsequently, different archetype buildings, one for each typology, have been implemented in the 3Muri environment [18] in order to derive their structural response through non-linear static analyses. Finally, based on the main Engineering Demand Parameters obtained in the previous step, the estimation of the EAL is performed according with the Italian guidelines seismic risk classification. The results in terms of monetary losses are then discussed to derive preliminary considerations on the economic and social impacts of probable seismic scenarios. A complementary study regarding the Reinforced Concrete (RC) residential buildings located in the examined area has been recently carried out [19].

2 OVERVIEW OF THE CONVENTIONAL APPROACH FOR THE ESTIMATION OF EXPECTED ANNUAL LOSS

The guidelines approved by the High Council of Public Works [16] define the methods addressing the seismic risk classification of constructions and the effectiveness of strengthening interventions. In particular, a conventional method is proposed based on the identification of the seismic performances towards four predefined limit states, namely Operational (SLO), Damage Limitation (SLD), Life Safety (SLV) and Collapse (SLC) [16]. The main novelty of the conventional method is represented by the introduction of two further conventional limit states: the Initial Damage (ID), resulting in a slight initial damage to the structural components and occurring for seismic events featuring a 10 years return period (Tr) and the Reconstruction limit state (RLS), referring to seismic events causing a monetary loss corresponding to the total value of the construction [20].

The seismic risk class of the building is defined as the minimum between two classes: the IS-V class, associated to the Safety Index of the structure at the Life Safety Limit State, and the EAL class. The Safety Index is calculated as the ratio between $PGA_{C,SLV}$ (PGA related to the capacity of the building at the Life Safety Limit State) and $PGA_{D,SLV}$ (demand PGA prescribed by the code at Life Safety Limit State). The EAL-based score is related to the performances of the structure in terms of seismic losses (namely percentage of Expected Losses towards the total cost of the building, %RC) at different return periods T_r (namely Mean Annual Frequency of Exceedance, MAFE). More in details, the MAFE (λ) is calculated according to Equation (1):

$$\lambda = \frac{1}{T_{rC}} = \frac{1}{T_{rD}\left(PGA_D / PGA_C\right)^{1/0.41}} \tag{1}$$

where T_{rC} and T_{rD} are the return periods related to capacity and demand respectively.

The guidelines [16] also provide conventional %RC, properly calibrated to include all the repair actions associated to a specific damage level.

Figure 1 shows the entire procedure for the EAL index calculation. First of all, a pushover analysis is required to assess the building performances at the four pre-defined limit states (SLO, SLD, SLV and SLC, Figure 1b). At this point, the Multiple Degrees of Freedom (MDOF) System is converted to an equivalent single degree-of-freedom (SDOF) system (Figure 1c). Then, for each limit state, the PGA associated to the building capacity (PGA_C) can be calculated in the Acceleration Displacement Response Spectrum (ADRS) plane following the N2 method [21] (Figure 1d). In particular, the PGA_C is evaluated by scaling the response spectrum until the displacement demand matches the capacity at the reference limit state. Subsequently, based on the seismic hazard model adopted within the reference building code [22], the MAFE values corresponding to the mentioned limit states are determined (Figure 1e) and associated to the Expected Loss Ratios (%RC) prescribed in the guidelines [16]. For what concerns the ID limit state, an Expected Loss Ratio equal to 0% has been conventionally associated to a MAFE value equal to 0.1. Similarly, for the RLS an Expected Loss Ratio equal to 100% has been conventionally associated to a MAFE value equal to that calculated for the SLC limit state. A loss curve (multi-linear function) in the MAFE vs Expected Loss Ratio domain is thus obtained (Figure 1f). Finally, the EAL is computed by integrating the mentioned loss curve. More details about the described procedure are reported in [20]. Table 1 shows the risk classes for safety and economic assessment according to the mentioned guidelines [16].

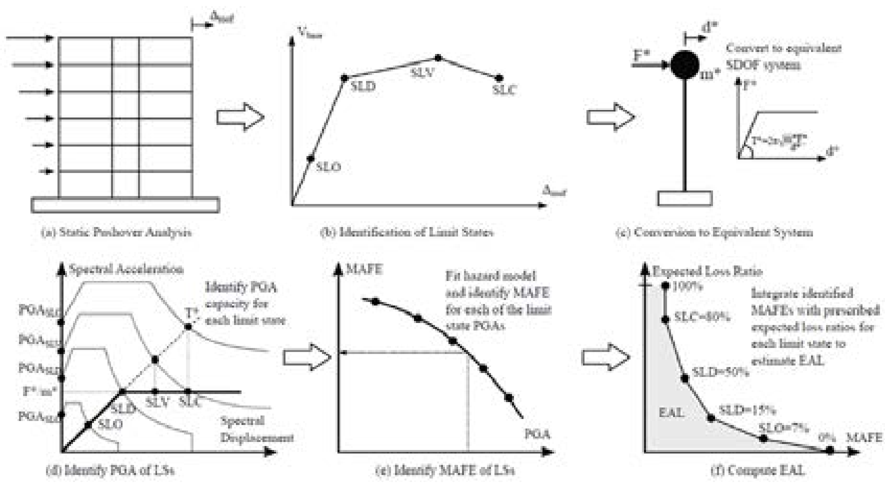


Figure 1: Steps of the Italian seismic risk classification scheme described in [23].

Safety assessment IS-V (%)	Economic assessment EAL (%)	Risk class
IS-V ≥ 100	EAL≤ 0.5	A+
80 ≤ IS-V < 100	0.5 ≤ EAL < 1.0	A
60 ≤ IS-V < 80	1.0 ≤ EAL < 1.5	B
45 ≤ IS-V < 60	1.5 ≤ EAL < 2.5	C
30 ≤ IS-V < 45	2.5 ≤ EAL < 3.5	D
15 ≤ IS-V < 30	3.5 ≤ EAL < 4.5	E
IS-V < 15	4.5 ≤ EAL < 7.0	F
	EAL ≥ 7.5	G

Table 1: Definition of risk classes as a function of both EAL and IS-V according to [16].

3 BUILDING TYPOLOGIES IDENTIFICATION FOR THE CITY CENTRE OF POTENZA

This work is carried out on the city of Potenza, located in Basilicata on a hill in the axial-active seismic belt (30 to 50 km wide) of southern Apennines. The city was hit by several strong earthquakes (intensity higher than or equal to VIII MCS). In particular, the 1826 and 1857 events caused severe damage in the entire town imposing a massive demolition and reconstruction activity in the historical city center [24]. In the aftermath of the Irpinia and Basilicata earthquake (November 1980), a massive reconstruction plan, funded by the Italian Government (law 219/81), involved several existing buildings in the Potenza municipality.

In this paper, the seismic assessment is referred to two main areas, namely the “old town center” and the “residential public housing neighborhood”, that can be considered as homogeneous zones (compartments) featuring specific historical, urbanistic and constructive peculiarities. Moreover, such compartments include most of the historical built heritage of the city, developed in two main periods: 1850-1950 and 1945-1990, respectively.

The specific building typologies inventory have been defined by combining the official national census database provided by the Italian Institute of Statistics (ISTAT) as the primary source for the classification of the building stock [25], integrated through secondary sources of information represented by extensive documental and virtual analysis and specific building surveys [26], [27]. More in details, a comprehensive documental analysis has been carried out based on the large database provided by the local organization of Social Housing (Azienda Territoriale per l’Edilizia Residenziale, ATER), directly involved in the residential compartment construction and in the post-seismic reconstruction after the Irpinia Earthquake (1980). Moreover, a number of building-by-building surveys, providing detailed data for both dimensional and structural peculiarities for a single building in an investigated area, have been performed. Finally, further information has been gathered interviewing local technicians with deep knowledge of the construction characteristics.

All that considered, the following main variables emerged as significant classification parameters: (i) masonry texture configuration (regular or irregular), (ii) horizontal structure typology (deformable, semi-rigid or rigid slab), (iii) presence of mixed structures (i.e. mixed masonry-RC structures), (iv) roof types, (v) presence of vaults, (vi) presence of seismic structural intervention. Based on the mentioned parameters, a preliminary macro-typologies inventory for the examined compartments has been defined, retrieving six macro-classes of masonry constructions (MUR).

The MUR1 and MUR2 typologies concern the first urban village built outside the historical center of the city in the 1920s. The MUR1 buildings feature squared local stone or solid brick masonries. Floors are mainly realized with hollow bricks and steel beams. The roof is pitched with wood structure and planking. This typology is characterized by the absence of vaults and mixed structures. Similar features have been retrieved for the MUR2 typology except for the vertical and horizontal structures, which are characterized by barely cut stone and vault floor with bricks and steel beams. The roof is pitched with brick-concrete slab. Over the years, some of the buildings included in the MUR2 typology have been subjected to strengthening interventions, consisting mainly of widespread connections (insertion of metal bars or RC beams). The MUR3 and MUR4 typologies, built in 1940-1960, group masonry constructions featuring solid brick masonry and lime mortar with rigid slab (reinforced brick-concrete) and connections between vertical walls and horizontal elements. In particular, the MUR4 typology is characterized by external masonry walls and internal RC beam-column systems. Both typologies show reinforced concrete pitched roof slab. The MUR5 and MUR6 typologies, built before 1920, are made of disorganized irregular stone masonry with friable mortar.

Such buildings have been retrofitted through different types of interventions (application of diffused tie-roads, filling the voids and/or cracks inside the wall by injecting of new mortar, substitution of damaged elements along cracking lines with new ones, etc.) performed after the Irpinia-Basilicata earthquake. The deformable slabs have been generally replaced by a rigid floor with reinforced brick-concrete slabs.

This preliminary inventory has been further refined considering other significant attributes emerged from the described documental and in situ investigations. Among those, irregularities in plan and the presence of connections between slabs and walls cannot be ignored for a comprehensive evaluation of the building typologies. In particular, based on the gathered data, masonry constructions in the investigated area can be grouped into three main classes: low-rise buildings “Lr” (1-2 stories), medium-rise buildings “Mr” (3-4 stories) and high-rise buildings “Hr” (5-6 stories). The mentioned number of stories ranges (1–2, 3–4, and 5–6) have been defined according with the considerations drown in [28]. Indeed, all other variables being equal, masonry buildings featuring one to two stories exhibit a similar seismic behavior [28]. A similar criterion can be adopted for medium- and high-rise buildings.

In this optic, seventy-two typologies have been finally identified from the classification approach discussed above, as shown in Table 2.

MACRO-CLASS	Number of stories			Shape in plan		Slab-wall connections		ID
	Lr	Mr	Hr	Reg.	Irreg.	C	Nc	
MUR1	x			x		x		MUR1, Lr, Reg, C
	x			x			x	MUR1, Lr, Reg, Nc
	x				x	x		MUR1, Lr, Irreg, C
	x				x		x	MUR1, Lr, Irreg, Nc
		x		x		x		MUR1, Mr, Reg, C
		x		x			x	MUR1, Mr, Reg, Nc
		x			x	x		MUR1, Mr, Irreg, C
		x			x		x	MUR1, Mr, Irreg, Nc
			x	x		x		MUR1, Hr, Reg, C
			x	x			x	MUR1, Hr, Reg, Nc
			x		x	x		MUR1, Hr, Irreg, C
			x		x		x	MUR1, Hr, Irreg, Nc
MUR2	x			x		x		MUR2, Lr, Reg, C
	x			x			x	MUR2, Lr, Reg, Nc
	x				x	x		MUR2, Lr, Irreg, C
	x				x		x	MUR2, Lr, Irreg, Nc
		x		x		x		MUR2, Mr, Reg, C
		x		x			x	MUR2, Mr, Reg, Nc
		x			x	x		MUR2, Mr, Irreg, C
		x			x		x	MUR2, Mr, Irreg, Nc
			x	x		x		MUR2, Hr, Reg, C
			x	x			x	MUR2, Hr, Reg, Nc
			x		x	x		MUR2, Hr, Irreg, C
			x		x		x	MUR2, Hr, Irreg, Nc
MUR3	x			x		x		MUR3, Lr, Reg, C
	x			x			x	MUR3, Lr, Reg, Nc
	x				x	x		MUR3, Lr, Irreg, C
	x				x		x	MUR3, Lr, Irreg, Nc

		x		x		x		MUR3, Mr, Reg, C
		x		x			x	MUR3, Mr, Reg, Nc
		x			x	x		MUR3, Mr, Irreg, C
		x			x		x	MUR3, Mr, Irreg, Nc
			x	x		x		MUR3, Hr, Reg, C
			x	x			x	MUR3, Hr, Reg, Nc
			x		x	x		MUR3, Hr, Irreg, C
			x		x		x	MUR3, Hr, Irreg, Nc
	x			x		x		MUR4, Lr, Reg, C
	x			x			x	MUR4, Lr, Reg, Nc
	x				x	x		MUR4, Lr, Irreg, C
	x				x		x	MUR4, Lr, Irreg, Nc
		x		x		x		MUR4, Mr, Reg, C
MUR4		x		x			x	MUR4, Mr, Reg, Nc
		x			x	x		MUR4, Mr, Irreg, C
		x			x		x	MUR4, Mr, Irreg, Nc
			x	x		x		MUR4, Hr, Reg, C
			x	x			x	MUR4, Hr, Reg, Nc
			x		x	x		MUR4, Hr, Irreg, C
			x		x		x	MUR4, Hr, Irreg, Nc
	x			x		x		MUR5, Lr, Reg, C
	x			x			x	MUR5, Lr, Reg, Nc
	x				x	x		MUR5, Lr, Irreg, C
	x				x		x	MUR5, Lr, Irreg, Nc
		x		x		x		MUR5, Mr, Reg, C
MUR5		x		x			x	MUR5, Mr, Reg, Nc
		x			x	x		MUR5, Mr, Irreg, C
		x			x		x	MUR5, Mr, Irreg, Nc
			x	x		x		MUR5, Hr, Reg, C
			x	x			x	MUR5, Hr, Reg, Nc
			x		x	x		MUR5, Hr, Irreg, C
			x		x		x	MUR5, Hr, Irreg, Nc
	x			x		x		MUR6, Lr, Reg, C
	x			x			x	MUR6, Lr, Reg, Nc
	x				x	x		MUR6, Lr, Irreg, C
	x				x		x	MUR6, Lr, Irreg, Nc
		x		x		x		MUR6, Mr, Reg, C
MUR6		x		x			x	MUR6, Mr, Reg, Nc
		x			x	x		MUR6, Mr, Irreg, C
		x			x		x	MUR6, Mr, Irreg, Nc
			x	x		x		MUR6, Hr, Reg, C
			x	x			x	MUR6, Hr, Reg, Nc
			x		x	x		MUR6, Hr, Irreg, C
			x		x		x	MUR6, Hr, Irreg, Nc

Lr: low-rise buildings, Mr: medium-rise buildings, Hr: high-rise buildings, Reg: regular shape in plan, Irreg: irregular shape in plan, C: presence of slab-wall connections, Nc: absence of slab-wall connections.

Table 2: Building typologies inventory.

However, the number of masonry buildings actually included in some of the mentioned typologies classes is extremely limited. As a consequence, in order to reduce the computational efforts and also considering the slight incidence of a limited number of cases on the entire seismic assessment of the area, the typologies including a number of elements lower than three have been neglected. Seven typologies have been finally considered in what follows counting 213 buildings in total, distributed as reported in Table 3. For the sake of clarity, it is worth noting that, in this work, only isolated residential buildings have been taken into account. As a matter of fact, considering their inherent peculiarities, specific studies are needed for the seismic assessment of the historical-monumental and masonry aggregates located in the examined area. For the same reason, the MUR5 typology, composed by masonry aggregates, has not been included in Table 3.

Building typology	Number of buildings
MUR1,Hr,Reg,Nc	28
MUR3,Lr,Reg,C	20
MUR3,Mr,Reg,C	59
MUR3,Hr,Reg,C	31
MUR4,Mr,Reg,C	35
MUR4,Mr,Irreg,C	16
MUR6,Hr,Reg,C	24
Total	213

Table 3: Prevalent building typologies distribution.

4 CASE STUDIES

4.1 Archetype buildings

A series of archetype buildings, one for each typology, has been defined. The archetype referred to the first building typology (MUR1,Hr,Reg,Nc) is a five-story masonry building featuring a floor area equal to 317 m^2 (20.7 x 15.3 m) and a total height equal to 18 m (Figure 2). The vertical structure is composed by solid bricks, except for the first floor featuring an irregular stone masonry. The horizontal structure configuration consists in steel beams and hollow clay bricks. Three archetypes have been defined for the MUR3 building typology (Figures 3 to 5). The same dimensions in plan (23.4 x 12.4 m) have been adopted for all the mentioned archetypes, while different total height values have been considered: 7.1 m, 13.7 m and 20.3 m for “Lr”, “Mr”, and “Hr” building typologies, respectively. The vertical structure of the MUR 3 archetypes is composed by a solid brick masonry and lime mortar. On the other hand, RC floors with tie beams (connecting floors and masonry walls) have been adopted as horizontal structure. The building archetypes shown in Figure 6 and 7 are referred to MUR4. In both cases such archetypes feature a four-story mixed masonry-RC vertical structure. More in details, external masonry walls mixed with an internal RC beam-column system have been adopted. The MUR4 archetype buildings feature the same horizontal structure (reinforced brick-concrete floors) while differ in terms of plan configuration.

The last building prototype (Figure 8) refers to buildings located in the historical city center and involved in the reconstruction plan pursued in the aftermath of the Irpinia-Basilicata earthquake. The performances of the “ancient” masonry, characterized by disordered rubble stone with friable mortar and irregular sub-horizontal courses, were improved through widespread retrofit interventions (e.g., application of diffused tie-roads, injection grouting, damaged elements substitution, etc.). For what concerns the horizontal structure, the deformable timber floors without steel chains and RC tie-beams were replaced by rigid floors with reinforced brick-concrete slab. The latter configuration has been implemented in the numerical model describing the MUR6 archetype (see Section 4.2).

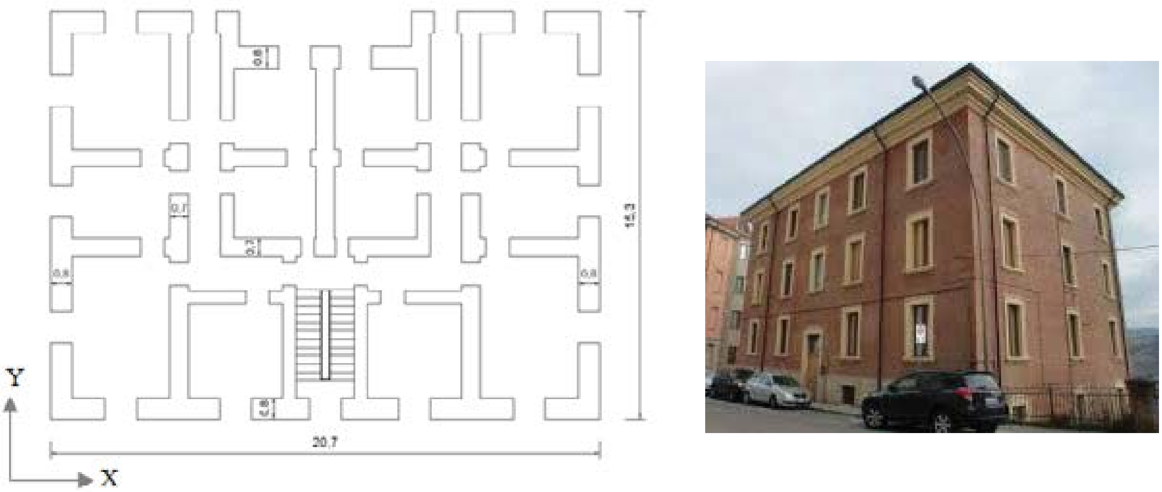


Figure 2: MUR1,Hr,Reg,Nc building typology: plan geometry of the first story (left) and a picture (right).

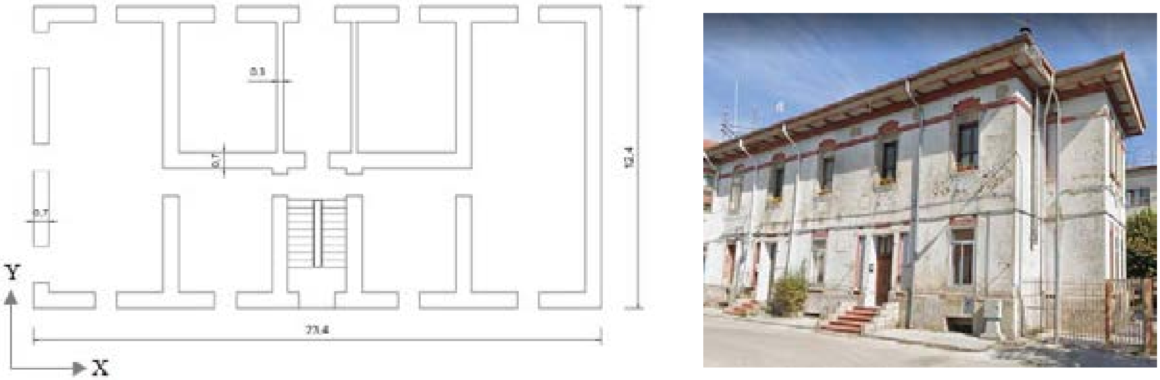


Figure 3: MUR3,Lr,Reg,C building typology: plan geometry of the first story (left) and a picture (right).

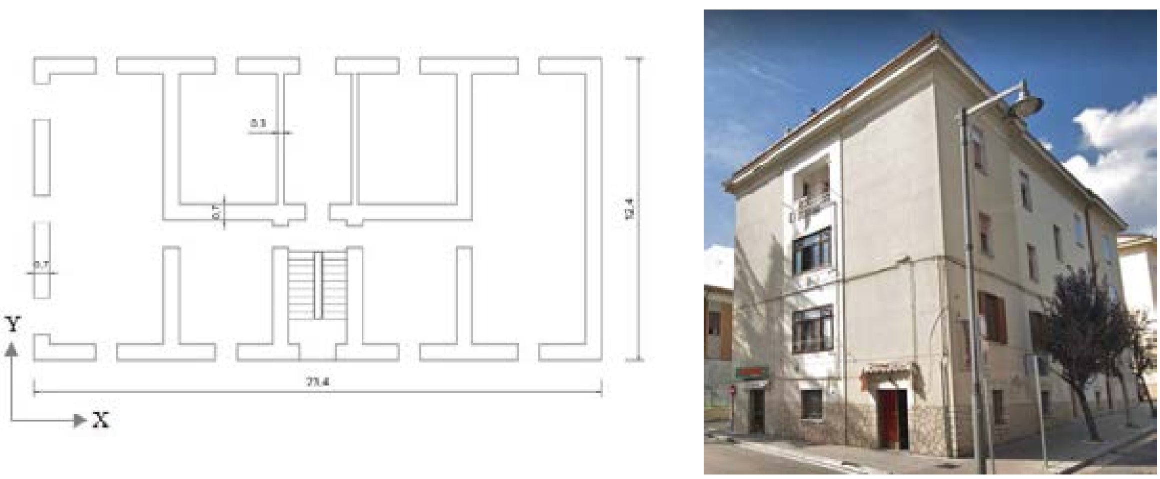


Figure 4: MUR3,Mr,Reg,C building typology: plan geometry of the first story (left) and a picture (right).

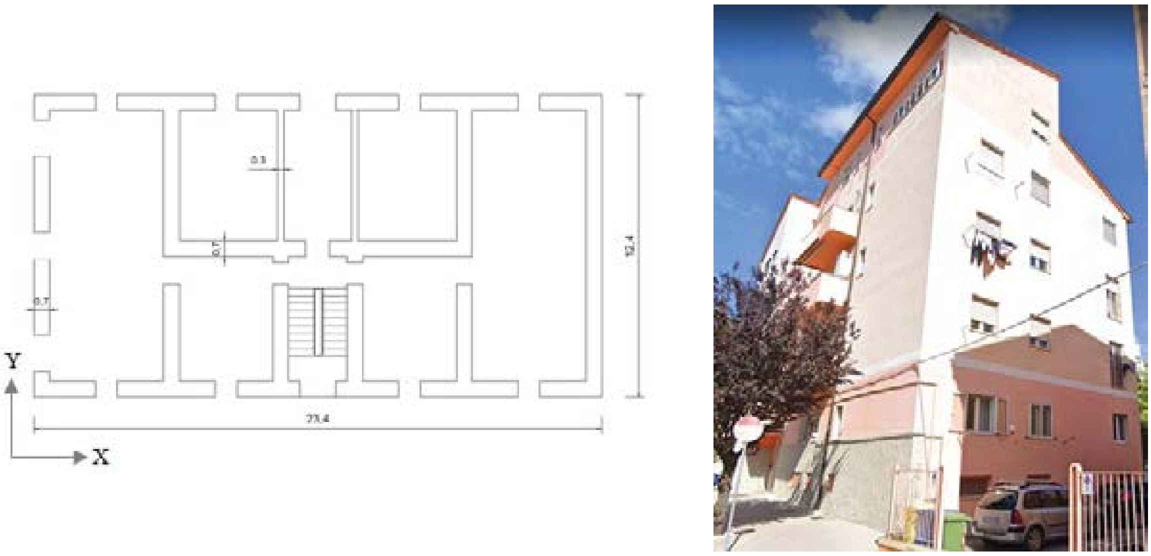


Figure 5: MUR3,Hr,Reg,C building typology: plan geometry of the first story (left) and a picture (right).

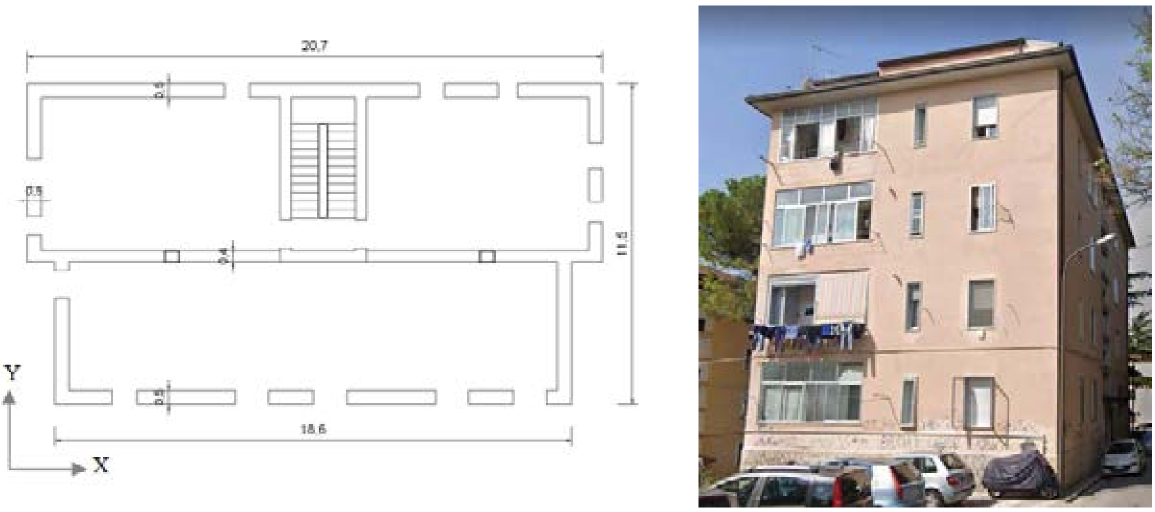


Figure 6: MUR4,Mr,Reg,C building typology: plan geometry of the first story (left) and a picture (right).

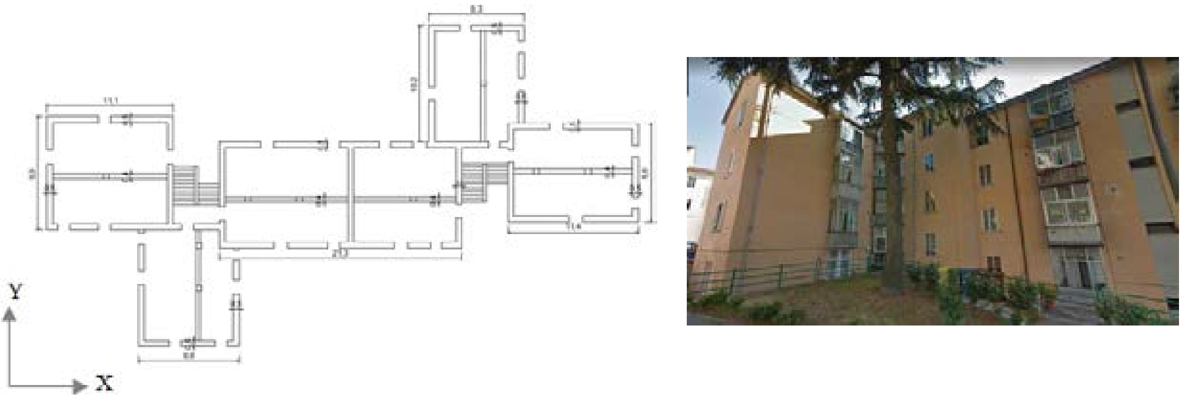


Figure 7: MUR4,Mr,Irreg,C building typology: plan geometry of the first story (left) and a picture (right).

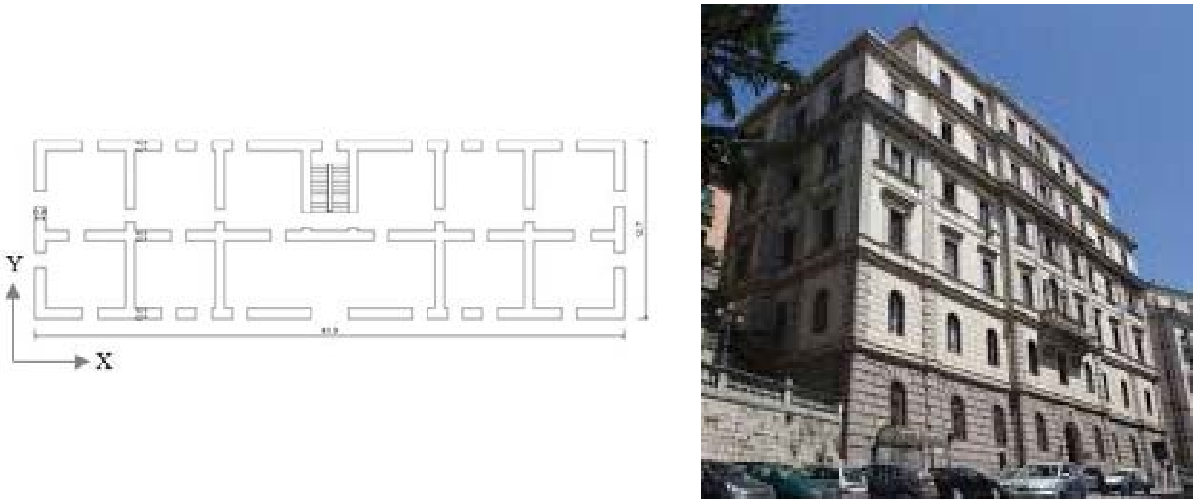


Figure 8: MUR6,Hr,Reg,C building typology: plan geometry of the first story (left) and a picture (right).

Generally speaking, the number of experimental campaigns aimed at the characterization of the mechanical properties of masonry is very limited if compared to the amount of data referred to concrete and reinforcements. As a matter of fact, the execution of exhaustive tests is frequently difficult due to both built heritage conservation issues and economic aspects [29]. Given the poor amount of data regarding the mechanical properties of the materials constituting the existing masonry buildings located in the examined area, reference to the typical values provided by the current Italian seismic code (Table C8.5.I [30]) have been taken into account. These values refer to historic masonry in poor conditions and have to be modified by corrective coefficients in the evidence of qualified characteristics, such as good mortar, presence of stringcourses etc.. Table 4 summarizes the values of the elastic and mechanical characteristics derived from the mentioned seismic code and adopted in the numerical models for irregular stone, barely cut stone and solid brick masonry panels.

Mechanical properties	Irregular stones	Barely cut stone	Brick and lime mortar
Comp. strength $f_{m,av}$ (MPa)	1.5	2	3.45
Shear strength $\tau_{0,av}$ (MPa)	0.025	0.043	0.09
Young modulus $E_{,av}$ (MPa)	870	1230	1500
Shear modulus $G_{,av}$ (MPa)	290	410	500

Table 4: Mechanical parameters adopted in the numerical models.

Finally, it is worth noting that all the archetype buildings are assumed to be located on a medium soil classified as soil type B, according with the current Italian seismic code [22]. For each archetype, the site hazard curve, defined based on the data provided by the INGV (Italian Institute of Geophysics and Volcanology), is expressed in terms of Mean Annual Frequency of Exceedance ($MAFE_i$) as a function of the considered IM, namely, the Peak Ground Acceleration (PGA).

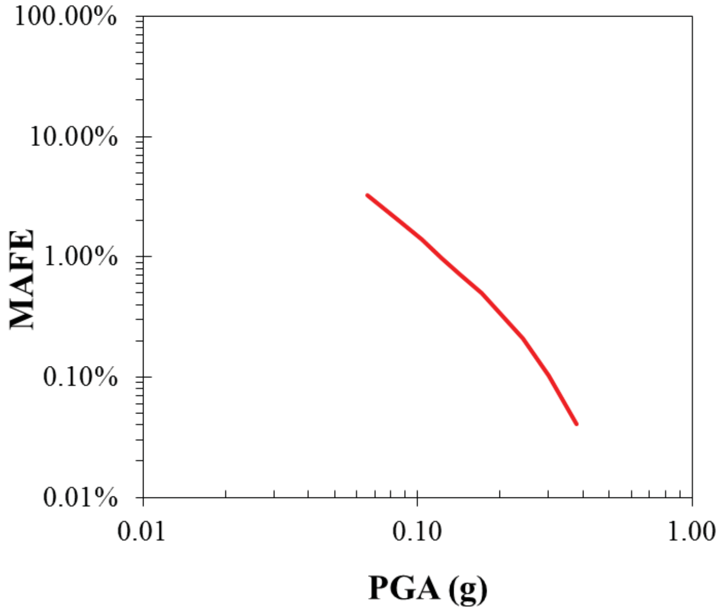


Figure 9: Hazard curve of the examined site, Potenza Soil Type B.

4.2 Numerical modeling

In order to assess the global behavior of the selected archetype buildings, 3d non-linear numerical models have been implemented in the 3Muri environment [18]. The mentioned software has been specifically developed for the evaluation of both local and global seismic response of URM buildings. 3Muri is based on the “Equivalent Frame Model” (EFM) approach. Generally speaking, a generic masonry wall with openings is idealized by identifying two main structural components, namely the piers and the spandrels, in which the non-linear response is concentrated, connected by a rigid area (nodes). The piers are the main vertically resisting elements while the spandrels couple the response of two adjacent piers. The identification of the geometrical properties of piers and spandrels is automatically performed by the software according to conventional criteria. The non-linear macro-element model implemented in 3Muri allows the two main failure modes, governing the response of masonry walls to be reproduced with a limited number of degrees of freedom. In terms of flexural behavior, rocking and crushing mechanisms are considered, whereas diagonal cracking and shear sliding are taken into account for shear failure. In order to define the ultimate shear and bending strength, simplified criteria are implemented in the software. The elastic behavior is defined considering the mechanical and geometrical properties of the masonry and a stiffness reduction factor is introduced to account for cracked conditions. It is worth noting that, in the numerical models of the archetypes included in the MUR4 building typology, the RC structural members have been modeled using non-linear lumped plasticity elements [18].

It is worth noting that the main assumption adopted in the numerical modeling is that the global behavior of the mentioned archetypes is fundamentally governed by the in-plane behavior of walls. In other words, the local mechanisms (mainly out-of-plane mechanisms) are not taken into account. This assumption is considered acceptable for most of the examined archetypes (namely all the archetypes except MUR1), since the systematic presence of RC ring beams is expected to reduce the vulnerability to local mechanisms [31]-[33]. The numerical models of the selected building prototypes are represented in Figure 10. As can be observed, the presence of staircase has been neglected at this step of the study.

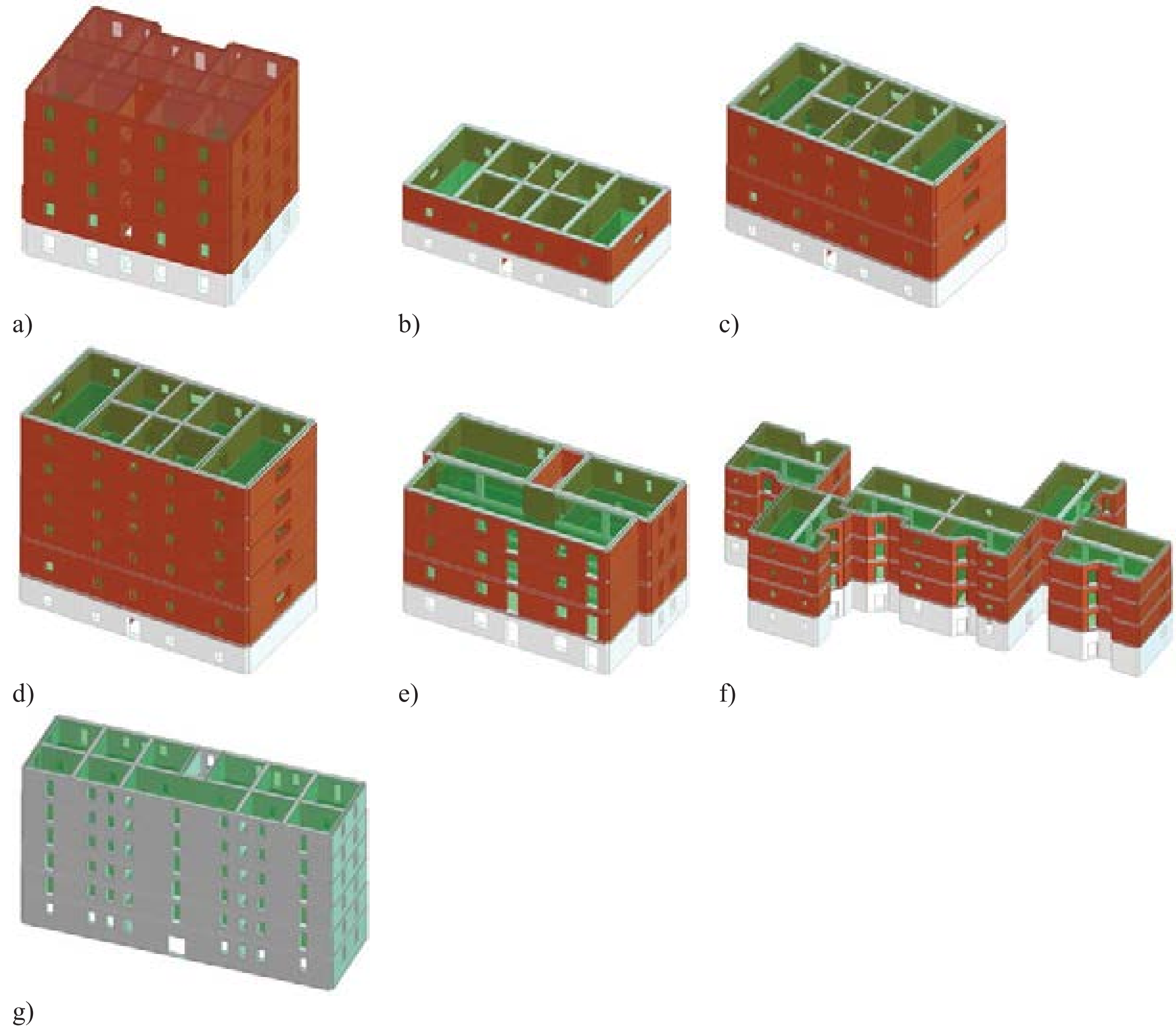


Figure 10: 3D view of the building typologies: a) MUR1,Hr,Reg,Nc; b) MUR3,Lr,Reg,C; c) MUR3,Mr,Reg,C; d) MUR3,Hr,Reg,C; e) MUR4,Mr,Reg,C; f) MUR4,Mr,Irreg,C; g) MUR6,Hr,Reg,C.

4.3 Analysis Results

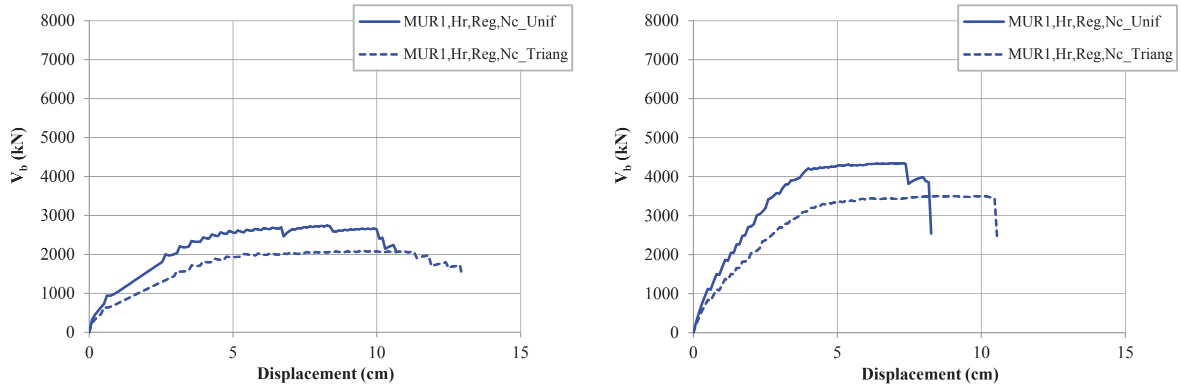
Modal analyses have been performed in order to derive the dynamic characteristics of the selected buildings. Table 5 resumes the fundamental periods (T) and participation masses (M) of the examined numerical models. Each building prototype features similar fundamental periods along the principal directions. The lower period obtained with the MUR4 typology is probably associated to the contribution provided by the internal RC beam-column systems.

Building typology	T_x (s)	M_x (%)	T_y (s)	M_y (%)
MUR1,Hr,Reg,Nc	0.50	66	0.49	81
MUR3,Lr,Reg,C	0.17	77	0.18	72
MUR3,Mr,Reg,C	0.30	80	0.35	78
MUR3,Hr,Reg,C	0.49	78	0.56	78
MUR4,Mr,Reg,C	0.31	63	0.48	80
MUR4,Mr,Irreg,C	0.45	30	0.44	58
MUR6,Hr,Reg,C	0.53	69	0.63	78

Table 5: Modal parameters.

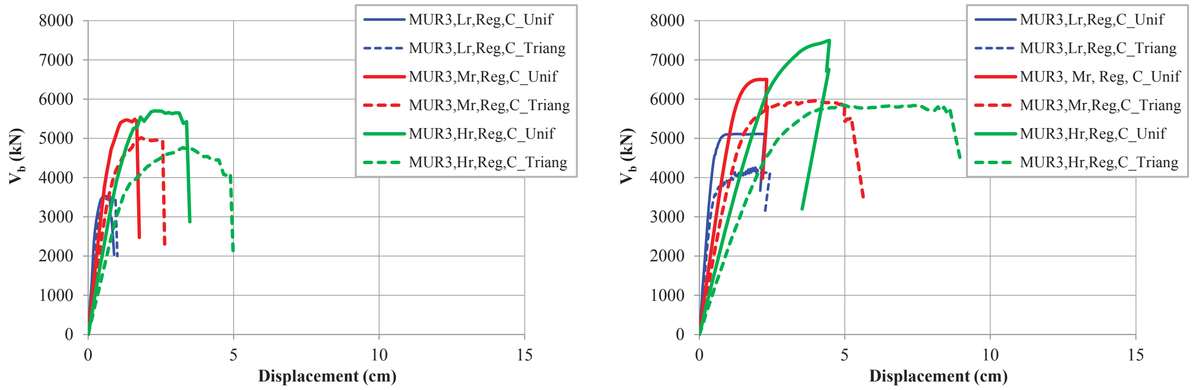
Non-linear seismic analyses have been performed along the main (X- and Y-) directions of the archetype buildings considering two different force distributions: (i) uniform ("Unif") distribution, proportional to the mass, and (ii) linear ("Triang") distribution, proportional to the shape of the fundamental mode of vibration.

Figure 11 to Figure 14 show the pushover curves in the two principal directions of each archetype. It is worth noting that the capacity curves in terms of base shear vs. top displacement have been cut off at a peak strength reduction of about 20% on the negative slope.



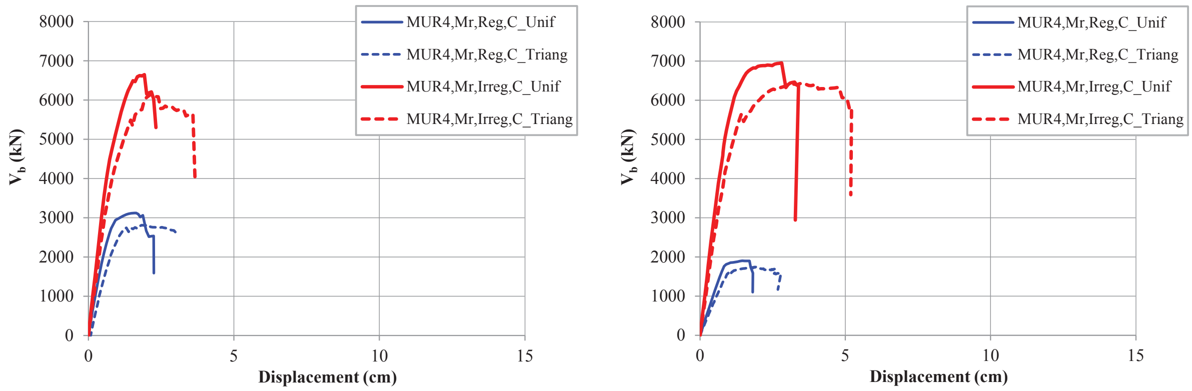
a) b)

Figure 11: Pushover curves of the selected MUR1 building typology: a) X direction; b) Y direction.



a) b)

Figure 12: Pushover curves of the selected MUR3 building typologies: a) X direction; b) Y direction.



a) b)

Figure 13: Pushover curves of the selected MUR4 building typologies: a) X direction; b) Y direction.

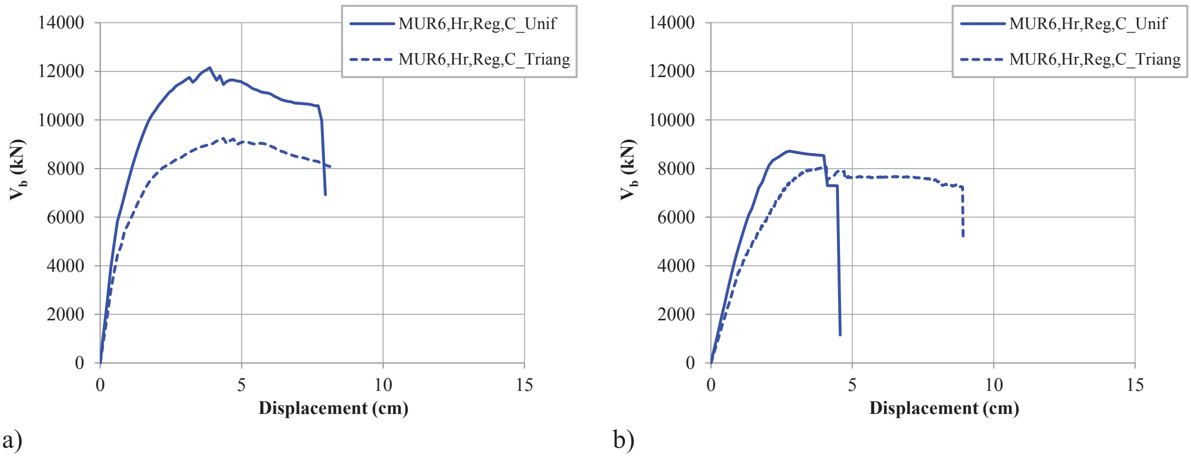


Figure 14: Pushover curves of the selected MUR6 building typologies: a) X direction; b) Y direction.

A different structural response has been obtained by using the two mentioned distributions. Obviously, the top displacement being equal, the maximum strength registered using the uniform distribution is larger than that obtained using the triangular distribution (the resultant of horizontal forces applied at each step of the analysis in the "Unif" distribution is double with respect to that associated to the "Triang" distribution). Moreover, while the uniform pattern produces a force concentration at first floor, a redistribution of loads is obtained with the triangular pattern, thus leading to a larger ductility capacity (of about 50%) of the examined structures. For the archetype buildings associated to MUR1 and MUR3, the lower value of the peak strength is registered in the X-direction (Figures 11 and 12). This is probably due to a lower number of resistant elements coupled with large openings along such direction. For what concerns the MUR4 archetypes, the more uniform distribution of openings and the presence of interior resistant elements (RC frames) counterbalance the structural response (in terms of peak strength) along the two main directions (Figure 13). For the MUR6 archetype, the larger value of the peak strength observed in the X-direction seems to be associated to the presence of a continuous internal masonry wall (with limited openings) along this direction (Figure 14). Finally, it is worth noting that the weakest structural response in terms of strength capacity has been observed for MUR1 and MUR4 archetype buildings. In the first case, such result seems to be related to the poor mechanical properties of the structural materials, compared to those of the remaining archetypes. On the other hand, for what concerns the MUR4 typology, the limited number of vertical resisting elements (in particular along the Y-direction) significantly affects the peak strength values.

Figure 15 to Figure 21 plot the damage patterns of the examined archetypes associated to the final step of the analysis. Different colors have been adopted to represent the failure modes of the involved structural elements.

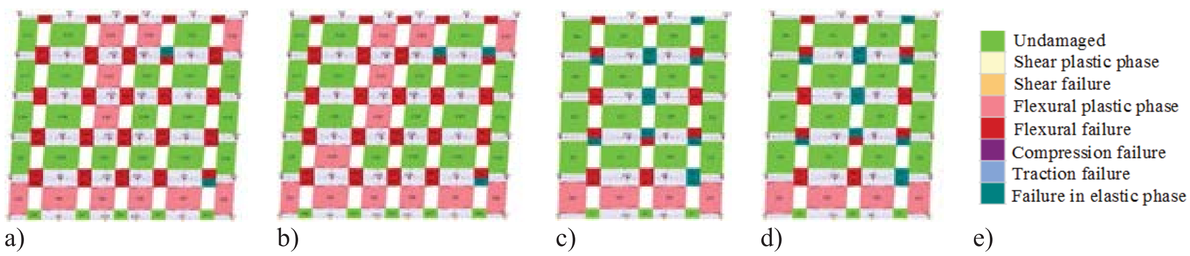


Figure 15: Damage pattern on the MUR1,Hr,Reg,Nc building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.

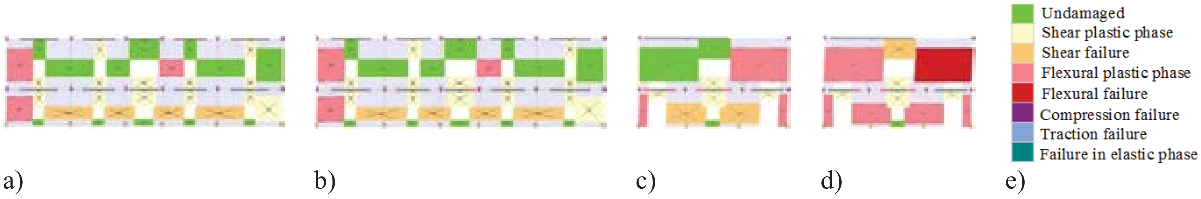


Figure 16: Damage pattern on the MUR3,Lr,Reg,C building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.

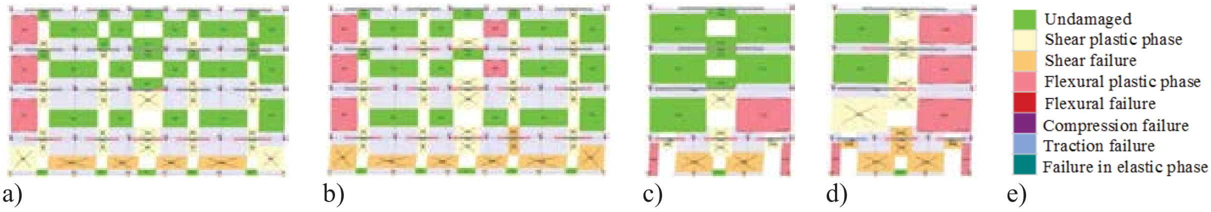


Figure 17: Damage pattern on the MUR3,Mr,Reg,C building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.

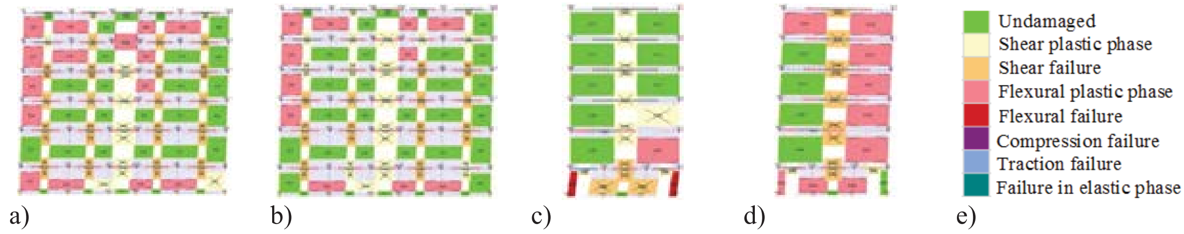


Figure 18: Damage pattern on the MUR3,Hr,Reg,C building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.

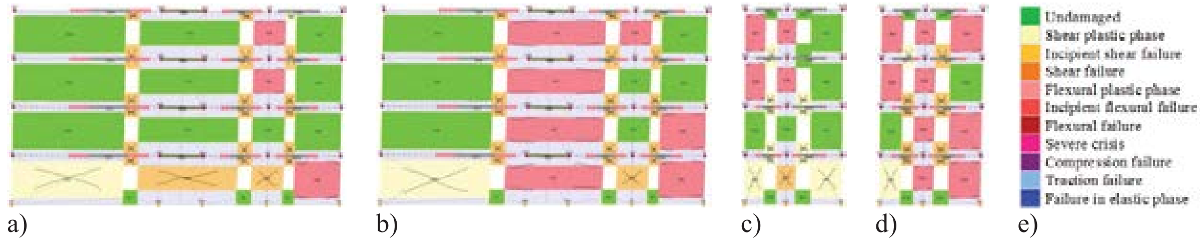


Figure 19: Damage pattern on the MUR4,Mr,Reg,C building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.

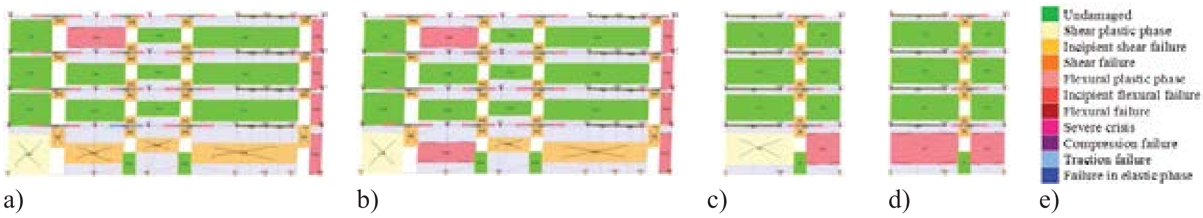
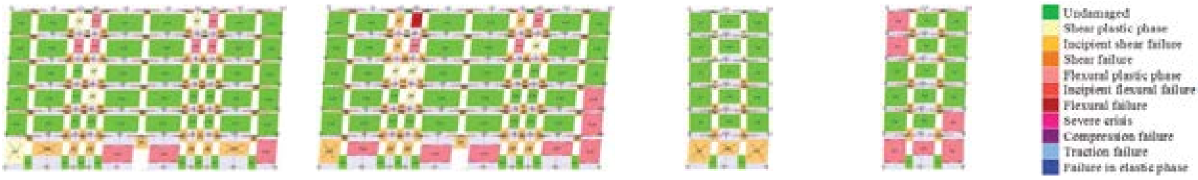


Figure 20: Damage pattern on the MUR4,Mr,Irreg,C building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.



a) b) c) d) e)

Figure 21: Damage pattern on the MUR6,Hr,Reg,C building: a) and b) front facade wall, respectively, for uniform and triangular load pattern; c) and d) side wall, respectively, for uniform and triangular load pattern; e) legend of the damage states associated to each masonry element.

The damage of the MUR1,Hr,Reg,Nc archetype building (Figure 15) is characterized by the flexural failure of spandrels triggering a strong piers-weak spandrel mechanism and, as a consequence, a rocking failure mode of piers [34]. In particular, the poor mechanical properties of the ground floor masonry produce a concentration of the flexural damage at the first story. Conversely, for what concerns the MUR3 and MUR4 archetypes, the RC floors with tie beams located at each level of the structure directly affect behavior of spandrels leading to a shear failure mode of such elements (Figures 16 to 20). Moreover, the rigid translation of the RC floors activates story mechanisms associated with shear collapse of the piers. Once again, the first story elements appear as the most vulnerable elements. A similar behavior has been observed for the MUR6 archetype building. However, the enhanced mechanical properties of such building typology lead to a reduced damage in the structural elements with respect to those observed for MUR3 and MUR4 archetypes. Finally, as mentioned above, the redistribution of loads associated to the triangular distribution corresponds to a redistribution of damage along the height of the examined buildings.

5 EXPECTED ANNUAL LOSS ESTIMATION

The conventional approach proposed within the Italian Seismic Risk Classification [16] and described in Section 2, has been applied to evaluate the “seismic quality” of the examined archetypes. For each archetype, the procedure has been performed four times (one for each non–linear analysis, i.e. two different load patterns coupled with two different main directions). The main outputs of the mentioned procedure are summarized in Table 6 and Table 7. It is worth noting that only the results corresponding to the non–linear analysis leading to the maximum value of EAL are reported. In particular, the return periods (Tr) and MAFE (λ) values for each target limit state are shown. The EAL values in the as-built configuration are provided in the third column of Table 7 and are expressed as a percentage of the Replacement Cost (RepC) of the building. The latter parameter has been estimated as the average cost of demolition and construction per square meter of similar new buildings, assumed equal to 954 €/m^2 according with [1].

Building typology	$T_{r, SLO}$ (years)	λ_{SLO} (%)	$T_{r, SLD}$ (years)	λ_{SLD} (%)	$T_{r, SLV}$ (years)	λ_{SLV} (%)	$T_{r, SLC}$ (years)	λ_{SLC} (%)
MUR1,Hr,Reg,Nc	65	1.54	30	3.33	211	0.47	393	0.25
MUR3,Lr,Reg,C	30	3.33	30	3.33	297	0.34	419	0.24
MUR3,Mr,Reg,C	75	1.33	30	3.33	139	0.72	233	0.43
MUR3,Hr,Reg,C	30	3.33	30	3.33	170	0.59	338	0.30
MUR4,Mr,Reg,C	36	2.78	30	3.33	87	1.15	147	0.68
MUR4,Mr,Irreg,C	46	2.17	30	3.33	119	0.84	207	0.48
MUR6,Hr,Reg,C	65	1.54	30	3.33	211	0.47	393	0.25

Table 6: Return periods (Tr) and MAFE (λ) values for each target limit state.

Building typology	RepC	$EAL_{As\text{-}built}$ (%RepC)	$EAL_{Retrofitted}$ (%RepC)
MUR1,Hr,Reg,Nc	1,812,848	1.60	1.0
MUR3,Lr,Reg,C	553,625	1.41	0.5
MUR3,Mr,Reg,C	1,107,251	1.45	0.5
MUR3,Hr,Reg,C	1,660,876	1.47	0.5
MUR4,Mr,Reg,C	908,399	1.89	1.0
MUR4,Mr,Irreg,C	2,207,556	1.67	1.0
MUR6,Hr,Reg,C	3,045,912	1.32	0.5

Table 7: $EAL_{As\text{-}built}$ and $EAL_{Retrofitted}$ values.

The results in terms of $EAL_{As\text{-}built}$ are in line with the considerations regarding the structural response of the examined buildings made in Section 4.3. As a matter of fact, the weak structural response observed for MUR1 and MUR4 archetypes produced larger values of EAL. On the contrary, lower values of EAL have been observed for the remaining archetypes, in particular for the MUR6 typology.

A general understanding of the potential socio-economic effects of the seismic scenarios at territorial scale has been obtained by monetizing the $EAL_{As\text{-}built}$ values, obtained for the each typology, with respect to the effective corresponding Replacement Cost (RepC). The monetary expected annual loss of the two compartments has been calculated by multiplying, for each building typology, the monetized $EAL_{As\text{-}built}$ value for the total number of elements of this category. As reported in Table 8, the total expected annual loss of the entire compartments (i.e., area's expected annual loss, AEAL) is equal to approximately 483 million Euros. To give some reference for the mentioned value, the latter can be compared to the area's total income (ATI) obtained multiplying the per capita income (PCI) measured in the examined area in the last year (equal to €16,522 [25]), by the total number of occupants (equal to 5730). In this optic, the ratio between AEAL and ATI is equal to approximately 5 (483 million divided by 94.7 million Euros).

Recently, the Italian 2019 Financial Law [35], introduced the so-called "Sisma Bonus" providing incentives, in terms of tax deductions, for seismic strengthening interventions on private buildings. These tax deductions range from 50% to 85% of the retrofit intervention's total cost. The incentives system is directly related to the risk classes of the Italian seismic risk classification guidelines and is associated to specific ranges of EAL (see Table 1 in Section 2). In particular, a 50% tax deduction can be obtained by implementing retrofit interventions without class improvement with respect to the as-built configuration. It can be raised up to 75% and 85% in case of improvement of one or two seismic risk classes, respectively. In any case, the maximum retrofitting expenditure amounts to €96,000 per property unit (single family house, apartment, etc.). Moreover, following the recent COVID19 pandemic, a special "Super Bonus" [36] up to 110% has been issued, with maximum retrofitting expenditure per property unit raised up to €136,000 also allowing the assignment of credit solution. In other words, the accrued credit can be transferred to third parties (financial institutions, banks, lenders), limiting or avoiding the economic burden for the stakeholders.

In this optic, for each building typology, the monetary EAL values obtained considering potential retrofit interventions, aimed at the improvement of two seismic classes with respect to the as-built condition, has been calculated (see the third column of Table 8). The reduction of EAL for each building typology ($\Delta EAL = EAL_{As\text{-}built} - EAL_{Retrofit}$) is also reported (last column of Table 8). The total variation of the EAL ($\Delta AEAL$) is thus equal to €264,440,931.

Assuming that all the buildings' owners exploit the maximum retrofit expenditure amount (i.e., 136,000 per property unit), the total cost of the potential interventions is equal to € 311,712,000. Therefore, less than two years would be sufficient to pay back the entire amount of the financial resources involved in the seismic protection improvement of the examined area's built heritage.

Building typology	$EAL_{As\text{-}built}$ (€)	$EAL_{Retrofitted}$ (€)	ΔEAL (€)
MUR1,Hr,Reg,Nc	81,215,592	50,759,745	30,455,847
MUR3,Lr,Reg,C	15,612,233	5,536,253	10,075,980
MUR3,Mr,Reg,C	94,725,285	32,663,892	62,061,394
MUR3,Hr,Reg,C	75,686,112	25,743,576	49,942,537
MUR4,Mr,Reg,C	60,090,581	31,793,958	28,296,623
MUR4,Mr,Irreg,C	58,985,896	35,320,896	23,665,000
MUR6,Hr,Reg,C	96,494,496	36,550,945	59,943,551
AEAL	482,810,195	218,369,264	264,440,931

Table 8: Monetized EAL values estimated for the examined building typologies.

6 CONCLUSIONS

The seismic loss assessment of masonry building stock located in the historical city center of Potenza has been performed based on the conventional approach currently used within the Italian Seismic Risk Classification [16]. First of all, the masonry buildings detected on the examined territory have been grouped in 7 typologies. Subsequently, 7 archetype buildings, each one featuring the structural, material and geometrical peculiarities of the corresponding building typology, have been modeled in the 3Muri environment. At this point, the mentioned simplified approach has been performed to derive the EAL of each archetype (i.e. building typology). The socio-economic effects of the seismic scenarios at territorial scale have been assessed, in first approximation, by comparing the EAL of the entire examined area with the current Area's Total Income (ATI) of the actual population. The ratio between EAL and ATI is equal to approximately 5.

Finally, considering the recent economic strategy adopted by the Italian Government to gradually reduce the seismic vulnerability of the existing building stock, a potential global retrofit intervention, aimed at the improvement of two seismic risk classes for all the masonry buildings located in the examined area, has been considered. The potential global intervention could significantly reduce the direct EAL of about 50%, from 483 to 218 million Euros. Moreover, considering that the maximum total amount of the intervention is equal to approximately 310 million of Euros, the pay-back period (namely the time needed to recover the cost of the investment) is about 1.2 years. Obviously, further studies, implementing specific retrofit interventions for each archetype, should be performed in order to precisely evaluate the actual economic effects and the structural performances in the retrofitted configuration. Moreover, further building typologies (historical-monumental and masonry aggregates) should be included to obtain a general understanding and a complete definition of the socio-economic impact at the territorial scale.

AKNOWLEGMENTS

This research has been developed within the PON-AIM 2014-2020 project, "Attraction and International Mobility", Line 1, supported by the Italian Ministry of University and Public Instruction.

REFERENCES

[1] D. Cardone, A. Flora, B. Manganelli, Cost-benefit analysis of different retrofit strategies following a displacement based loss assessment approach: a case study. *Tenth U.S. National Conference on Earthquake Engineering Frontiers of Earthquake Engineering*, Anchorage, Alaska, USA, July 21-25, 2014. DOI: 10.4231/D3CF9J706.

[2] D. Cardone, A. Flora, M. De Luca Picione, A. Martoccia, Estimating direct and indirect losses due to earthquake damage in residential RC buildings. *Soil Dyn. and Earth. Eng.,* **126,** 2019. DOI: 10.1016/j.soildyn.2019.105801.

[3] M. Vona, A. Flora, E. Carlucci, E. Foscolo, Seismic Retrofitting Resilience-Based for Strategic RC Buildings. *Buildings*, **11**, 111, 2021. DOI: 10.3390/buildings11030111.

[4] M. Vona, Proactive Actions Based on a Resilient Approach to Urban Seismic Risk Mitigation. *Open Constr. Build. Technol. J.*, **14**, 321–335, 2020. DOI: 10.2174/1874836802014010321.

[5] D. Ottonelli, S. Cattari, S. Lagomarsino, Displacement-Based Simplified Seismic Loss Assessment of Masonry Buildings. *Journal of Earthquake Engineering*, **24**:sup1, 23-59, 2020. DOI: 10.1080/13632469.2020.1755747.

[6] J. Snoj, M. Dolšek, Pushover-based seismic risk assessment and loss estimation of masonry buildings. *Earthquake Engng Struct Dyn*., **49**, 567–588, 2020. DOI: 10.1002/eqe.3254.

[7] B. Borzi, H. Crowley, R. Pinho, Simplified pushover-based earthquake loss assessment (SP-BELA) Method for masonry buildings. *Int J Architect Heritage: Conserv, Anal Restor.,* **2**(2–4), 353-376, 2008. DOI: 10.1080/15583050701828178.

[8] J.K. Bothara, J.B. Mander, R.P. Dhakal, R.K. Khare, M.M. Maniyar, Seismic performance and financial risk of masonry houses. *ISET J Earthq Technol*., **44**(3–4), 421-444, 2007.

[9] K.A. Porter, An Overview of PEER's Performance-Based Earthquake Engineering Methodology. *9th International Conference on Applications of Statistics and Probability in Civil Engineering*, 273(1995), 973–980, San Francisco, California, 2003.

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

[11] K. A. Porter, J.L. Beck, Shaikhutdinov, R.V. Simplified estimation of economic seismic risk for buildings. *Earthquake Spectra*, 20(4), 1239–63, 2004. DOI: 10.1193/1.1809129.

[12] D. Cardone, G. Perrone, A. Flora, Displacement-Based Simplified Seismic Loss Assessment of Pre-70S RC Buildings. *Jour. of Earth. Eng.*, **24**:*sup1*, 82-113, 2020. DOI: 10.1080/13632469.2020.1716890

[13] G.Perrone, D. Cardone, G.J. O'Reilly, T.J. Sullivan, Developing a direct approach for estimating expected annual losses of Italian buildings. *Jour. of Earth. Eng.***,** 1–32, 2019. DOI: 10.1080/13632469.2019.1657988.

[14] C.M. Ramirez, E. Miranda, Building specific loss estimation methods & tools for simplified performance based earthquake engineering. Technical Report No. 171, John A. Blume Earthquake. Engineering Center, 2011, Stanford University.

[15] T.J. Sullivan, G.M. Calvi, Considerations for the seismic assessment of buildings using the direct displacement-based assessment approach. Proc. of the ANIDIS Conference, 2011, Bari, Italy.

[16] Ministry Decree n.58 28/02/2017 Allegato A: linee guida per la classificazione del rischio sismico delle costruzioni (in Italian). Italian Ministry of Infrastructures and Trasport, Italy. http://www.mit.gov.it/normativa/decreto-ministeriale-numero-58-del-28022017.

[17] EU Council. Council Directive 92/75/EEC of 22 September 1992 on the indication by labelling and standard product information of the consumption of energy and other resources by household appliances. Brussels, Belgium; 1992.

[18] S. Lagomarsino, A. Penna, A. Galasco, S. Cattari, TREMURI program: an equivalent frame model for the nonlinear seismic analysis of masonry buildings. *Engineering Structures*, **56**, 1787–99, 2013. DOI: 10.1016/j.engstruct.2013.08.002.

[19] A. Flora, D. Cardone, M. Vona, G. Perrone, A Simplified Approach for the Seismic Loss Assessment of RC Buildings at Urban Scale: The Case Study of Potenza (Italy). *Buildings*, **11**, 142, 2021. DOI: 10.3390/buildings11040142.

[20] E. Cosenza, C. Del Vecchio, M. Di Ludovico, M. Dolce, C. Moroni, A. Prota, E. Renzi, The Italian guidelines for seismic risk classification of constructions: technical principles and validation. *Bulletin of Earthquake Engineering*, **16,** 5905–5935, 2018. DOI: 10.1007/s10518-018-0431-8.

[21] P Fajfar, A nonlinear analysis method for performance based seismic design. *Earthq Spectra*, 16, 573–592, 2000.

[22] D.M. 17 Gennaio 2018 (D.M. 2018). Technical code for constructions (in Italian). G.U. n. 42 del 20/2/2018. Rome, Italy.

[23] G.J. O'Reilly, D. Perrone, M. Fox, R. Monteiro, A. Filiatrault, Seismic assessment and loss estimation of existing school buildings in Italy. *Engineering Structures*, **168**, 142–162, 2018. DOI: 10.1016/j.engstruct.2018.04.056.

[24] F.T. Gizzi, N. Masini, Historical earthquakes and damage patterns in Potenza (Basilicata, Southern Italy). *Annals of geophysics,* **50**(5), 2007.

[25] Italian National Statistics Institute (ISTAT). 15th National Census on Buildings and Population. 2014, Rome, Italy (in Italian).

[26] C. Iacovino, A. Flora, D. Cardone, M. Vona, Defining a masonry building inventory for the city of Potenza. *20th International Conference on Computational Science and Applications (ICCSA 2020)*, LNCS 12250, 914–927, 2020. DOI: 10.1007/978-3-030-58802-1_65.

[27] A. Flora, C. Iacovino, D. Cardone, M. Vona, Typological inventory of residential Reinforced Concrete buildings for the city of Potenza. *20th International Conference on*

Computational Science and Applications (ICCSA 2020), LNCS 12250, 899–913, 2020. DOI: 10.1007/978-3-030-58802-1_64.

[28] M. Polese, M. Di Ludovico, A. Prota, G. Tocchi, M. Gaetani d'Aragona, Utilizzo della scheda Cartis per aggiornamento dell'inventario ed effetto sulle stime di vulnerabilità a scala territoriale, *XVIII Convegno Anidis*, Ascoli Piceno, 15-19 settembre 2019. (In Italian).

[29] G. Milani, M. Valente, Failure analysis of seven masonry churches severely damaged during the 2012 Emilia-Romagna (Italy) earthquake: non-linear dynamic analyses vs conventional static approaches. *Eng Fail Anal*, **54**, 13–56, 2015. DOI: 10.1016/j.engfa ilana l.2015.03.016.

[30] MIT 2019, Circolare n. 7 del 21 gennaio 2019. Istruzioni per l'applicazione dell'Aggiornamento delle "Norme tecniche per le costruzioni" di cui al decreto ministeriale 17 gennaio 2018.

[31] J. Milosevic, S. Cattari, R. Bento, Definition of fragility curves through nonlinear static analyses: procedure and application to a mixed masonry-RC building stock. *Bulletin of Earthquake Engineering*, **18**, 513–545, 2020. DOI: 10.1007/s10518-019-00694-1.

[32] G. Magenes, A. Penna, I. Senaldi, M. Rota, A. Galasco, Shaking table test of a strengthened fullscale stone masonry building with flexible diaphragms. *J Archit Herit Conserv Anal Restor*, **8**(3), 349–375, 2014. DOI: 10.1080/15583 058.2013.82629 9

[33] D. D'Ayala, E. Speranza, An integrated procedure for the assessment of seismic vulnerability of historic buildings. *In: Proceedings of the 12th European conference on earthquake engineering*, London, 2002.

[34] P. Foraboschi, Coupling effect between masonry spandrels and piers. *Materials and Structures*, **42**, 279–300, 2009. DOI: 10.1617/s11527-008-9405-7.

[35] Law 145/2018. In Bilancio di Previsione dello Stato per l'Anno Finanziario 2019 e Bilancio Pluriennale per il Triennio 2019-2021 (Legge di Bilancio 2019); n.302 del 31/12/2018; Gazzetta Ufficiale della Repubblica Italiana: Roma, Italy, 2018. (In Italian).

[36] Law 77/2020. In Conversione in Legge, con Modificazioni, del Decreto-Legge 19 Maggio 2020, n. 34, Recante Misure Urgenti in Materia di Salute, Sostegno al Lavoro e all'Economia, Nonche' di Politiche Sociali Connesse all'Emergenza Epidemiologica da COVID-19; n.180 del 18/07/2020; Gazzetta Ufficiale della Repubblica Italiana: Roma, Italy, 2020. (In Italian).