MULTISOURCE DATA APPROACH FOR SEISMIC FRAGILITY ASSESSMENT OF MASONRY BUILDINGS AT REGIONAL SCALE

C. Tosto[1], V. Leggieri[2], S. Ruggieri[1] & G. Uva[1]

[1] DICATECH Department, Polytechnic University of Bari, Bari, Italy

[2] School of Architecture and Design (SAAD), University of Camerino, Ascoli Piceno, Italy,
valeria.leggieri@unicam.it

Abstract: *The paper presents an approach for the assessment of seismic fragility for recurrent masonry building typologies in historical centres on a regional scale based on multisource data. At this scale of analysis, the poor level of information and the huge number of existing masonry buildings represent a twofold problem that needs to be addressed. In this view, the proposed framework starts from an integration of multisource data with different degrees of detail (e.g., regional landscape plans, public topographic datasets, census data and information provided by the CARTIS catalogue) directly implemented in GIS environment, obtaining a proper georeferenced database. This georeferenced informative structure is processed to derive geographic distribution, morpho-typological and structural features about masonry building typologies in historical centres. Subsequently, sets of mechanical models, sufficiently representative of the most widespread typologies on the regional territory, have been obtained by varying some significantly parameters coherently with available information. Capacity/Demand ratio has been estimated for each model of sets by implementing nonlinear static analysis for increasing levels of Peak Ground Acceleration. Finally, typological fragility curves have been derived for each set of buildings according to Multiple Stripe Analysis method. An application has been proposed for the case study of Puglia region, allowing to obtain a georeferenced informative structure useful for the investigation of architectural typological parameters that influence structural behavior and for the characterization of seismic vulnerability of a large portion of the masonry building stock of historical centre at regional scale.*

1 Introduction

Existing masonry buildings (URM) are among the most vulnerable in the built environment being generally designed without any seismic standards and, hence, unable to withstand forces induced by an earthquake as demonstrated by devastating effects induced by seismic events. Moreover, the built heritage of historical centers, which is nearly exclusively made up of masonry buildings frequently arranged in aggregate form, makes this problem more obvious. The huge amount of this segment of real estate and the pressing need to improve their performance levels and minimize potential damages and socioeconomic losses, imply large-scale preliminary investigation through suitable strategies to provide a synthetic estimation of the current structural and seismic performances useful to prioritization and planning of more detailed analyses, optimizing the available resources. Indeed, traditional building-level methods are unfeasible for this scale of analysis due to highly computational efforts and extremely detailed data required. Instead, focus should be placed on streamlining of processes, minimizing the necessary information and computational burden while maintaining a reasonable accuracy and reliability of the results (Pelà 2018). In this operation it needs to deal with a dual issue: on one hand, partial or total lack of data typical of ancient URM in historical centres, that often are the results of an historical evolution consisting in restoration operations, additions of parts, destination changes, damages and repairs, etc.; on the other hand, the computational power required by advanced structural modelling and analysis techniques widely adopted in several studies and application available in literature (D'Altri *et al.* 2019). In this view, two questions must be addressed: (a) the construction of an appropriate path of knowledge and information structure about features of the built fabric of historical centers; and (b) the development of procedures capable of performing effectively seismic vulnerability analyses based on limited information and low computational burden.

Regarding the first issue, to get beyond the obstacles of unavailability and difficulty in finding necessary information, large-scale data collection procedures continue to be developed exploiting different types of sources. Depending on the scale and scope of the evaluation, it is possible to rely on different information databases (Leggieri *et al.* 2022; Polese *et al.* 2019): ISTAT dataset (ISTAT 2011) is suitable for analyses at both national and local levels giving general information about the existing buildings in aggregate form for sub-urban areas; orthophotos, satellite photos together with territorial and landscape plans, represent another significant sources, providing basic information about various regional and sub-regional areas, in addition, technical cartographies and urban plans include information about morphology and geometry of built fabric on a urban scale. It is worth to highlighted that these massive volumes of data require a suitable tool that enabling the storage, systematization, integration and handling of all the informative layers to obtain a georeferenced database quickly and easily processable and searchable. With this in mind, a proper alternative is represented by geographic information system environment (GIS) allowing to manage different types of datasets, generally, already available in georeferenced format (e.g., shape, rater, etc), thereby facilitating the creation of an informative structure that can be applied to various large-scale seismic vulnerability assessment procedures (Columbro *et al.* 2022; Giovinazzi *et al.* 2021; Leggieri *et al.* 2022; Ramirez Eudave *et al.* n.d.; Villani *et al.* 2023). In addition, further information can be derived from interview-based procedures and expeditious surveys that allow to collect more detailed data about typological-structural characteristics of existing building stock. Several methodologies have been proposed in the last decades (Baggio *et al.* 2007; GNDT 1994; Uva *et al.* 2016, 2019; Zuccaro *et al.* 2016); among the other, CARTIS procedure (Zuccaro *et al.* 2016), created by the Italian Civil Protection Department as part of the RELUIS project, collects information about recurring typological-structural building classes within homogeneous urban sectors (TC) with the support of experienced local technicians and this catalogue can be easily implemented together with other datasets in GIS environment after a proper digitalization. The realization of such an informative structure is a kay step to implement any large-scale procedures; as a matter of fact, several proposals available in literature adopt the common strategy to categorize buildings with similar overall performance in typological-structural classes defined by few recurring characteristics according to specific taxonomies and typological catalogues. Despite this type of approach is now largely used and a lot of taxonomies are available for classify the building typologies (Lang et al. 2018, Brzev et al. 2013; Grünthal 1998), very few applications specifically related to definition of historical center typologies have been developed (Caniggia & Maffei 2008; National Group for Defense Against Earthquakes (GNDT) 1999; Tosto *et al.* 2023).

Moving to the second issue, the complex nature of the seismic and structural behavior of masonry structures calls for the application of advanced and burdensome numerical techniques based on a thorough knowledge of a construction. However, it needs to remember that such an approach is unfeasible for large-scale applications being impossible to obtain detailed knowledge and implement sophisticated modelling and analysis for all the individual buildings. This leads to the necessity for appropriate procedures quickly and affordably implementable for a large number of structures. In this perspective, firstly, it must be selected a proper approach among the three classical ones, namely: empirical approach, based on statistical analysis of observed damage; analytical-mechanical approach, that implies numerical modelling and analysis for sets of numerical models representative of certain building classes; hybrid approaches that combine the two aforementioned procedures (Calvi *et al.* 2006). Moreover, whatever the approaches, it is possible to make more efficient the implementation for large-scale applications by means of proper automated procedures (Leggieri *et al.* 2021; Ruggieri *et al.* 2021, 2023).

A further remark regards the necessity to select an effective synthetic indicator that may characterize the seismic vulnerability of architectural heritage. Fragility curves, describing the probability of exceeding a particular state of interest, identifying through specific thresholds in terms of different monitoring parameters generally defined as engineering demand parameter (EDP) by varying ground motion intensity measures (IM) (e.g., peak ground acceleration, or PGA) (Baker 2015). There are numerous suggestions in the literature about the development of fragility curves for Italian masonry structures (Donà *et al.* 2021; Lagomarsino & Cattari

2014; Lazzerini *et al.* 2023; Rosti *et al.* 2021; Ruggieri *et al.* 2023; Sandoli *et al.* 2021), generally, based on certain typological classes and statistic processing of the outcomes.

Within this broad context, the present work proposes a method for estimating the seismic fragility of the most widespread URM typologies in historical centers on a regional scale. The methodology uses multiple information sources implemented and integrated in GIS environment to perform, as crucial first step, a preliminary recognition regarding the peculiar feature of build fabric of municipalities' oldest nucleus. The aim of this first stage is to classify the historical centers according to a proper taxonomy and identify the most widespread URM typology as defined in a specific abacus throughout a whole regional territory. This is possible by using the CARTIS form, compiled for a sample of municipalities, in order to connect the historical centres macro-classes (HC-mcs), assumed coincident with the oldest TC as defined in CARTIS, to URM typologies of the abacus, compared with the CARTIS masonry typological building classes (MUR). Then, for each of the most recurrent URM typology, a typological-mechanical approach proposed by Ruggieri et al (Ruggieri *et al.* 2023) is performed to derive related fragility curves, by generating sets of numerical models obtained as combinations of numerical values falling within the ranges of certain parameters chosen from the abacus accounting for model uncertainty. Then, the capacity in terms of PGA has been computed for all the models of a set by mean of nonlinear static analysis and the capacity/demand (C/D) ratios are calculated for increasing level of PGA. The outcomes have been fitted according to the procedure suggested by Baker (Baker 2015) to derive typological fragility curves. A practical application, proposed for the case study of the Puglia region, demonstrated that the procedure can be quickly implement based on minimal set of information and readily expanded to different territorial contexts.

2 General overview of methodology

The proposed approach starts from a preliminary collection of multisource data properly handled and integrated in a georeferenced information system (GIS) environment (Leggieri *et al.* 2022) to classify the historical centres of a regional territory according to a specific taxonomy (Tosto *et al.* 2023) and, successively, identify the most widespread URM building typologies according to a proper regional abacus. Then, the seismic typological fragility curves are derived implementing the mechanical-typological approach proposed by Ruggieri et al (Ruggieri *et al.* 2023). The general framework, illustrated in Figure 1, is structured according three following phases:

1. Multisource data collection, handling and integration in GIS environment, and construction of a multi-layer georeferenced database;
2. Classification of the historical centres on a regional scale and identification of URM archetypes, properly matched to identify the most widespread URM building typologies;
3. Derivation of seismic fragility curves for the URM archetypes by means of a typological-mechanical approach.

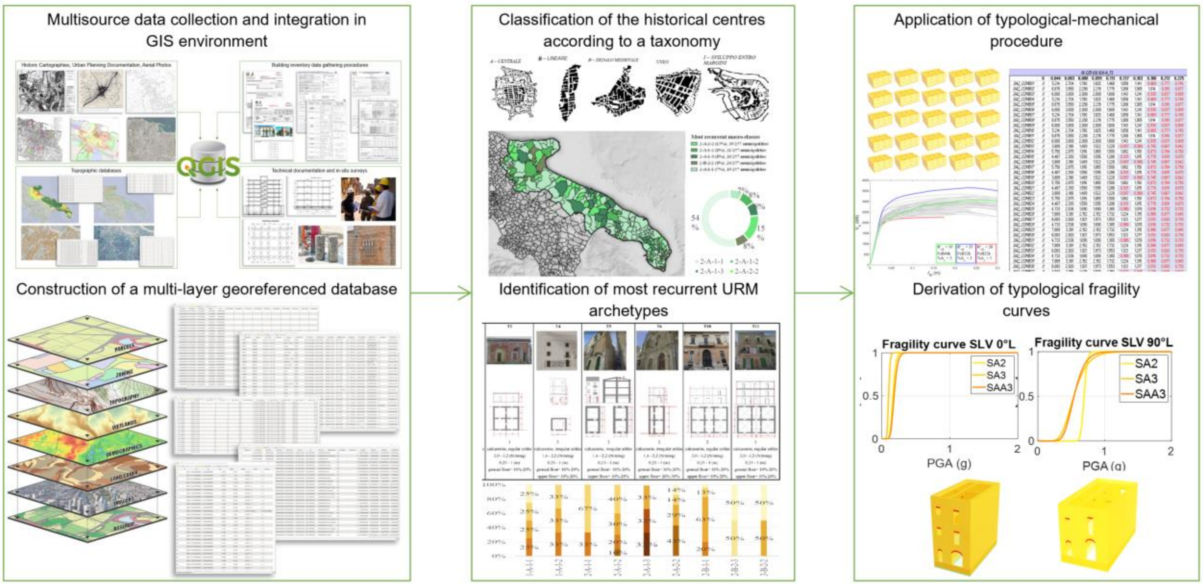

Figure 1: General framework of the methodology.

2.1 Multisource Data collection handling and integration

The preliminary kay phase implies the research and gathering of all the possible information sources about the features of historical centre macro-classes (HC-mcs) and related architectural heritage. ISTAT georeferenced database contains aggregate data about several general characteristics of existing buildings within census sections for the whole national. Simple queries of data about structural material and age of construction allow a preliminary identification of historical centre within a municipal territory focusing only on those census sections where most of the buildings have masonry structure and age of contraction dates back before 1945; the results are then checked and refined by means of rapid visual survey performed by means of satellite orthophotos, that allow to collect further essential information about morphology of built fabric of ancient nucleus of each municipality properly allocated in a related layer. Other important information sources are represented by territorial and landscape plans made freely available in georeferenced format for an entire region area, giving fundamental information about different components sub-regional areas characterized by homogeneity in terms of historical, morphological, and economic points of view. Peculiar geometrical and morphological characteristics of urban fabric are derived from urban plans and technical cartographies which contain data referred to aggregates or buildings. All these georeferenced databases are directly imported and managed in GIS environment creating an information structure composed by different layers.

The subsequent step regards the study of recurrent structural, geometrical and morpho-typological features of URM buildings to identify, within a proper abacus (Tosto *et al.* 2023), the most representative archetypes for an entire historical centre. To do this, it is possible to exploit CARTIS catalogue (Zuccaro *et al.* 2016), by focusing on oldest homogeneous town compartment (TC) assuming coinciding with historical centre and extrapolating the features of the related masonry building typologies (MUR).

2.2 Classification of historical centre on a regional scale and identification of URM archetypes

The integration and processing of data are performed in GIS environment using ISTAT database as base layer; indeed, the information extrapolated from rapid visual survey on satellite orthophotos, territorial, landscape and urban plans and technical cartographies is properly encoded according to reference historical centre macro-classes (HC-mcs) of a specific taxonomy (Tosto *et al.* 2023) and then associated to each municipality in the ISTAT attribute table. In this way it is possible automatically classify all the historical centres of the whole regional territory into the HC-mcs of the taxonomy.

The following operation is based on CARTIS database compiled for a sample of municipalities and containing consistent information about percentages and features of MURs in TCs. The analysis is limited to the oldest TC generally coincident with the oldest nucleus of the municipalities; therefore, each MUR of TC is recognized as one among the building archetypes of the typological abacus depending essentially on geometrical features of mean area floor and number of floors. The result is a direct association between the HC-mc of a municipalities and archetypes identified in the abacus. Consequently, it is possible a prelaminar estimation of prevailing archetypes within regional territory by taking into account the percentage distributions of corresponding MURs in each TC.

2.3 Derivation of regional seismic fragility curves

Seismic fragility curves are derived for the most widespread archetypes, as identified previously, by implementing a typological-mechanical approach proposing by Ruggieri et al. 2023. For each archetypes a set of models is constructed by varying and combining the values v_j of some parameters P_i properly selected among those available in the abacus. As a result, the total number of models N_m of each set is obtained as follow:

$$N_m = \prod_{j=1}^{n} \prod_{i=1}^{p} v_j(P_i) \cdot P_i \qquad (1)$$

Where n is the number of numerical values v_j for each parameter, and p is the number of the selected parameters P_i.

Numerical modelling and analysis are carried out by means of software POR2000 (“Newsoft POR2000” 2020), that implement an equivalent frame method based on so-called POR method that assumes a box-like behavior, rigid slab, shear-type scheme with constrained rotations at the base and the top sections of piers and nonlinear mechanical response of the elements descripted by simplified bilinear perfectly elasto-plastic relation. For each set representative of an archetype, the capacities in term of PGA of all the models is computing by means of nonlinear static analysis in two main horizontal directions (0°, 90°) under inverse triangular horizontal load patterns with regard to the life-safety limit-state (LSLS) achieved when the first pier reaches a displacement equal to 75% of near-collapse limit-state displacement for ductile mechanism $d_{NC,D}$ (equal to 0.010 times the height of the panel). Then, the C/D ratios are calculated for discrete increment of PGA. Hence, fragility curve of an archetype is derived by fitting the ratio between models that exceed LSLS (models with C/D lower than 1) and the total number of models investigated for each PGA level, by employing the maximum likelihood method (Baker 2015) to compute median θ and dispersion β that define the fragility function according to the following equation:

$$N_m P(C < D|IM = x) = \Phi\left(\frac{\ln\left(\frac{x}{\theta}\right)}{\beta}\right) \quad (2)$$

where $\Phi(\cdot)$ is the standard normal cumulative density function (CDF) and x is a value of IM.

3 Application to a case study: Puglia region

An application of the approach is proposed for Puglia region in south Italy. The following datasets are used for the implementation of the procedure:

- ISTAT dataset;
- satellite orthophotos and google satellite base map;
- regional territorial landscape plan (PPTR);
- technical regional cartography (CTR);
- CARTIS catalogue.

According to the ISTAT dataset, Puglia region includes 257 municipalities, a first processing of data regard the identification of the census sections in which most of the buildings have masonry structure and were realized before the 1945 for delimiting the areas of analysis. Then, in the ISTAT attribute table has been added further fields populated with information useful for the classification of historical centres according to the taxonomy. The information about nucleus shape is obtained by visual inspection on satellite orthophotos and google satellite base map, classified according to three different configurations (Centralized, Linear, Open); the field of foundation period collects information about the age of early settlements (Ancient foundation-until 7th cent. AD, Medieval foundation-7th cent. – 15th cent., Modern foundation-16th cent. – 19th cent., Contemporary foundation-after 19th) taken from PPTR; finally, the last two fields contain information about in plan regularity and average size of urban blocks, collected by observing CTR and satellite photos. The information is proper encoded in order to implement an automatically classification of historical centres of all the municipalities according to the taxonomy. The result is reported in Figure 2 that shows maps of HC-mcs and percentage distributions of the most widespread HC-mcs on the Puglia region.

Subsequently, it has been used CARTIS catalogue, available for 14 municipalities of the Puglia region; for each municipality, the oldest TC is assumed coincident with the historical centre; hence, the recognition of the related MUR as one among the building archetypes of the typological abacus is performed by comparing geometrical features of mean area floor and number of floors. The results, summarized in Table 1, show that in many cases it is no possible a one-by-one correspondence; indeed, a MUR can be associated to more than one archetype of the typological abacus; this because the geometrical characteristics of a MUR are generally defined by means of range of possible values, whereas the geometry of an archetypes of the abacus is defined by means of a unique value assumed as the most probable. However, it is possible investigate which of the archetypes are the most widespread on a regional territory; in the case at hand, the archetypes "casa a schiera" type A, indicated as SA2, SA3, SAA3, turn out to be the most representative of built fabric of historical centres of the Puglia region, but also "casa a schiera" type B SA3 and "casa in linea" LA2 and LA3 show a non-negligible presence.

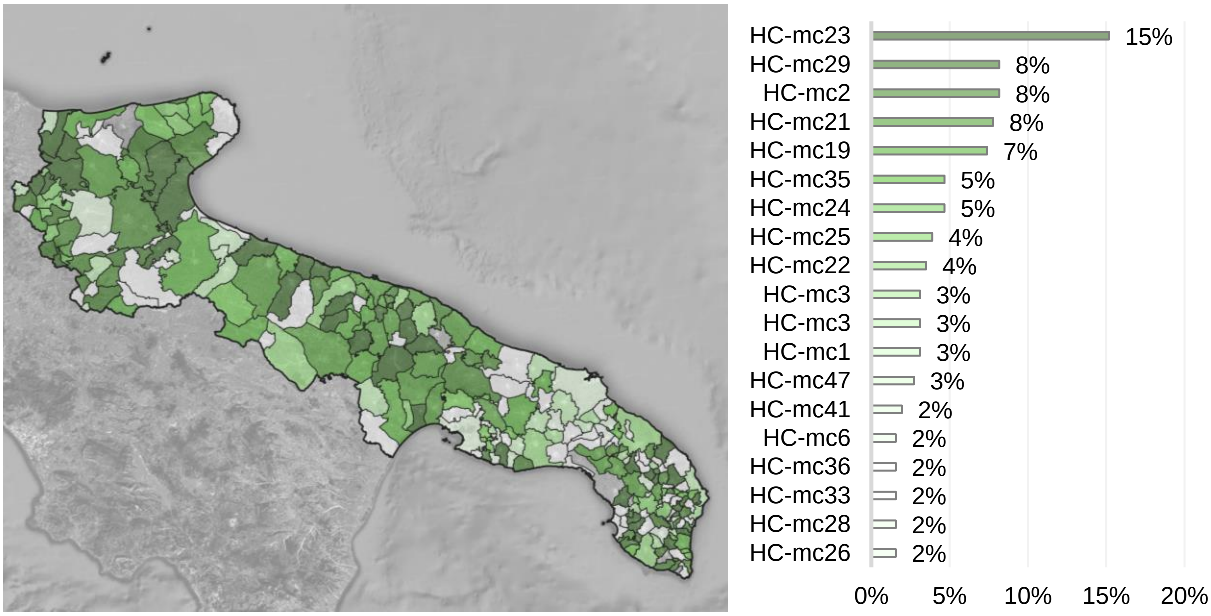

Figure 2. Maps of HC-mcs and percentage distributions of the most widespread HC-mcs on the Puglia region.

Table 1. Matching between HC-mcs and archetypes of the abacus based on CARTIS form.

HC-mc	**CARTIS municipalities**	**MUR1**		**MUR2**		**MUR3**	
		% in TC	**archetype**	**% in TC**	**archetype**	**% in TC**	**archetype**
HC-mc1	Bovino	60%	SA2/Cba	40%	SA2/SA3/SAA3	-	-
HC-mc2	Ruvo di Puglia	50%	SA2	50%	SA2/SA3/SAA3	-	-
HC-mc19	Castellaneta	60%	SA3/SAA3	40%	SA3	-	-
HC-mc20	Cisternino	50%	SA3/SAA3	50%	SA3/SAA3	-	-
	Foggia	50%	SA2	50%	SB3	-	-
	Locorotondo	50%	SA2/SA3/SAA3	50%	SA2/SA3/SAA3	-	-
HC-mc21	Andria	50%	SA2	50%	LA2/LA3/LB2	-	-
HC-mc23	Bisceglie	10%	SA2/SA3/SAA3	90%	SB2/SB3	-	-
	Faeto	100%	SA2/CBa			-	-
	Sant'Agata di Puglia	95%	SB3	5%	SB2/SB3	-	-
HC-mc25	Minervino Murge	50%	SA2	50%	SA2	-	-
	Vico del Gargano	30%	SA2	30%	SA2/CBa	40%	SA2/SA3/SAA3
HC-mc30	Erchie	30%	CBb	70%	Cba/CBb	-	-
HC-mc37	Carlantino	100%	SA2/CBa	-	-	-	-

3.1 Derivation of regional seismic fragility curves

Fragility curve is derived for the most recurrent archetypes, as identified in previous step, namely, SA2, SA3, SAA3, SB3, LA2 and LA3. As illustrated in section 2.3, for each archetype a set of models has been constructed assuming a fixed geometry in terms of dimensions in plan, mean area floor, number of floors and interstorey height as defined in the abacus, while varying and combining the values related to the three parameters of thickness of wall (P_5), compressive strength (coherently with masonry type) (P_6) and percentage of openings (P_7). For the sake of clarity, in Table 2 it is listed the parameters P_i and related values v_j of the typological abacus; in particular, for the thickness of wall has been assumed three couples of values, the first referred to external walls, the second referred to the internal walls; four couples of values of mean compressive strength $f_{c,m}$ mean tensile strength $f_{v,m}$ have been considered by discretizing a range defined with a minimum and maximum values as prescribed in Italian Building Code (Ministero delle Infrastrutture e dei Traspoti 2009) coherently with the tuff masonry type; the incidence of opening is taken into account in term of percentage of façade considering two possible values respectively for ground and upper floor. The result is a set composed by a total of 48 models for each archetype. For each model of a set nonlinear static analysis have been performed to compute the capacity C in terms of PGA for LSLS. Then, C/D ratios have been calculated for increasing values of demand D end, for each value of demand D, it has been computed the ratio between the number of models that exceed the LSLS, for which C/D is greater than 1, and the total number of models of the set. The obtained values have been fitted implementing the maximum likelihood method suggested by Baker (Baker 2015) to find the parameters of median θ and dispersion β. The results are summarized in Table 3 and the fragility curves for the analysed archetypes are shown in Figure 3.

Table 2. numerical values of geometrical and mechanical parameters of most recurrent URM architypes of the abacus.

Archetype	**P_1 dimensions in plan (m)**	**P_2 mean area floor (m^2)**	**P_3 umber of floors**	**P_4 interstorey height (m)**	**P_5 thickness of wall (m)**	**P_6 masonry type $f_{c,m}$-$f_{v,m}$ (MPa)**	**P_7 percentage of opening (%)**
SA2	6 x 12	72	2	3,5	50-25 80-50 100-50	Tuff Masonry 1,40-0.10 2,60-0,13 2,60-0,16 3,20-0,19	Ground floor 10-20 Upper floors 20-30
SA3	6 x 12	72	3				
SAA3	6 x 12	72	3				
SB3	10 X 12	120	3				
LA2	16 x 12	192	2				
LA3	16 x 12	192	3				

Table 3. Summary of median θ and dispersion β for the fragility curves of the most recurring building typologies

URM typology	**0° direction**		**90° direction**	
	θ	***β***	***θ***	***β***
SA2	0.1475	0.2091	0.5231	0.2988
SA3	0.0889	0.1841	0.4765	0.3028
SAA3	0.1637	0.2316	0.4919	0.3122
SB3	0.2816	0.2095	0.5897	0.2692
LA2	0.2038	0.2420	0.3523	0.2418
LA3	0.1264	0.1130	0.2588	0.3110

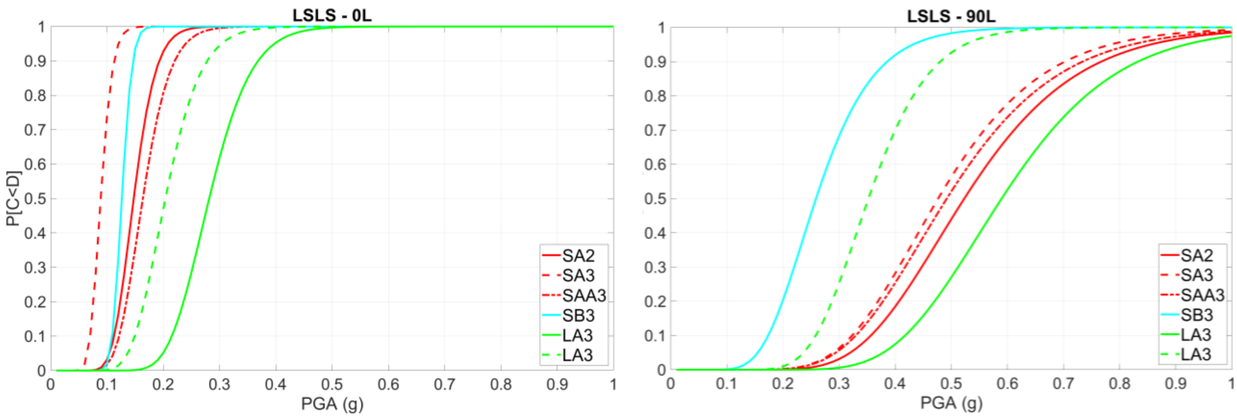

Figure 3. Seismic typological fragility curves with reference to LSLS, 0° and 90° direction of the most recurrent building archetypes.

4 Conclusions and future developments

The work presents a multisource data approach for seismic fragility assessment of masonry buildings at regional scale that enable to exploit the available datasets to gather and infer necessary information for seismic assessment of historical heritage on a regional scale. The general framework is organized into three subsequent phases: in the first one, various information sources are properly collected, integrated and processed in GIS environment constructing a georeferenced database about the features of historical centres and related URM typologies on a regional scale. Using such an informative structure, in the second phase it is implemented a classification of historical centres according to an accurate taxonomy and investigation about the presence of URM typology compared with archetypes as defined in a specific abacus. The aim of this process is to identify the most widespread URM typologies in historical centres, schematized by means of archetypes of a specific abacus through certain parameters useful for the implementation of the third step in which a typological-mechanical approach is used to derive fragility curves for the archetypes representative of the most recurring URM typologies in regional territory.

The application of the procedure to the case study of the Puglia region allowed a quick categorization of each municipality's historical center and the identification of the prevalent URM typology schematized as the archetypes of a specific abacus. This operation enables a rapid implementation of a typological-mechanical approach based on a minimal set of information for a preliminary estimation of seismic vulnerability on a regional scale.

The potential of the procedure is the possibility to rapidly investigate the distribution of URM typologies at the territorial scale, using limited data; this latter is also useful for seismic vulnerability assessment of archetypes representative of significant portion of the historical building heritage on a regional scale.

The work is a prelaminar study that represent a starting point for future advancements; in fact, despite in part already automated, all the process could be structured in a properly IT tool capable of gather available data, infer missing information, organize the informative structure, implement different type of assessment procedures and dynamically enrich the available datasets.

Sach a tool could be useful for public authorities and all the possible stakeholders involved in the process of recovery, retrofit and requalification in the view of seismic vulnerability and risk mitigation, to set up a preliminary investigation for effectively planning more detailed analysis according to a proper prioritization optimizing the available resource in terms of time and costs.

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