Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 1766-1778

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

A TYPOLOGICAL-MECHANICAL APPROACH TO ASSESS LARGE-SCALE SEISMIC FRAGILITY OF MASONRY BUILDINGS IN HISTORICAL CENTRES

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Abstract

The paper presents a mechanical approach for the assessment of large-scale seismic fragility for recurrent masonry building typologies in historical centres. Especially in the context of regional-scale analysis, the poor level of information drives analysts to develop suitable approaches to characterize in a synthetic way the seismic behaviour of the existing masonry building stock. Hence, the proposed framework arises from a matching between historical centres macro-classes and recurrent masonry building typologies defined by exploiting multi-sources data integration in GIS environment (e.g., census data, topographic cartographies, and information provided by the CARTIS form application). After, sets of mechanical models, which are sufficiently representative of the most widespread typologies on the regional territory, can be realized accounting for structural and morpho-typological features variability, as evincible from the available georeferenced database. Subsequently, nonlinear static analysis is adopted as analysis method where, for each model, Capacity/Demand ratio can be estimated for increasing levels of Peak Ground Acceleration. The obtained results are then processed according to Multiple Stripe Analysis method to derive typological fragility curves, which can be properly associated to historical centre macro-classes, covered by certain percentage of masonry building typologies. The proposed procedure was applied to the case study of Puglia region, allowing to investigate large portions of the building stock characterizing historical centres, by managing few information and by providing a methodology easily extendible to different context of applications.

Keywords: Seismic Fragility, Large-Scale Analysis, Seismic Vulnerability, Historical Centres, Building Typologies, Masonry Buildings.

Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10518.21031

1 INTRODUCTION

The disastrous consequences of seismic events occurred in the last decades have revealed the urgent need to intervene on existing building stock, which represents one of the most vulnerable elements in the built environment, being often designed in absence of any antiseismic standards or prescriptions. This issue is more evident for the built heritage of historical centres, almost entirely composed by masonry buildings and often organized in aggregate configuration. The huge amount of this portion of existing real estate, together with low knowledge level, requires a preliminary large-scale investigation through proper procedures, able to give a synthetic estimation of current structural and seismic performances based on few information. Hence, in this context, two types of questions have to be addressed: (a) the definition of a proper knowledge path and structure about the features of built fabric of historical centres; (b) the development and implementation of procedures able to perform efficiently seismic vulnerability analyses on the bases of few information.

With regard to the first issue, several methodologies are available in literature, based on a common approach aimed to identify typological building classes, as representative of the entire existing building stock, defined through few recurrent characteristics and by structuring taxonomies suitable for large-scale applications [1-5]. If on the one hand, taxonomies for the classification at large-scale of the existing building stock are largely widespread, on the other hand, few applications and proposals are still available with specific regard to historical building heritage, for which the definition of historical centres typologies results a hard task because of their complexity and heterogeneity. In this framework, a fundamental reference is the study conducted by Caniggia and Maffei [6] on which it was developed a survey-form based procedure named "Historical Centres Form" [7] that represents a first attempt to define historical centre typologies in a view of seismic vulnerability. It is worth pointing out that, when the investigation is focused on historical centres, often it needs to deal with unavailability or inaccessibility of information sources that force to take alternative solutions to obtain the necessary information. In addition, it should be considered that, for this scale of application, huge amount of data has to be gathered, managed and structured in order to be easily searchable and rapidly post-processed. In a such process, GIS environment represents a suitable tool allowing the integration and elaboration of different types of georeferenced information, making possible the construction of an informative structure useful for the implementation of different large-scale seismic vulnerability assessment procedures [8-13].

The second issue is connected to the complexity that characterize the structural and seismic behavior of masonry buildings typically organized in aggregate configuration, which requires sophisticated analytical-mechanical methodologies implemented on the basis of detailed knowledge of the structure investigated. It is evident that, such approach it is impracticable for large-scale applications due to a twofold reason: (i) the impossibility to achieve a detailed knowledge for all the buildings; (b) the significant computational burden required by such a kind of analysis. From these observations, it arises the need to have suitable procedures that are efficiently implementable in terms of time and costs for huge number of buildings. In this sense, in the last years several procedures have been proposed generally based on the use of automated processes [14-16].

In this wide context, a further issue is represented by the choice of an appropriate synthetic indicator, able to properly describe seismic vulnerability of built heritage. Among the others, the use of fragility curves is becoming increasingly widespread in the framework of large-scale applications, able to express the probability of exceeding a specific limit state of interest as a function of some ground motion intensity measures (e.g., spectral acceleration or peak ground acceleration, PGA) [17]. A lot of proposals with regard to fragility curves derivation for Italian masonry buildings are available in literature. The common starting point is the identification of building typological classes representative of large portions of existing building stock for which related seismic fragility is derived using different approaches. The mainly adopted procedure starts from empirical methods, which are based on a statistical elaboration of observed damage data for building classes [18-20]. An alternative approach is based on the implementation of analytical-mechanical methods for simulated sets of numerical models representative of building classes, [21-24]. Finally, some procedures implement hybrid seismic vulnerability assessment methods, combining the two abovementioned methodologies [25,26]. In each of these three approaches, the results are statistically processed and fitted for deriving fragility curves for building typological class. Latest studies propose an extension of these applications to derive overall fragility curves with regard to entire historical centres, urban areas, and regional territories [27-31].

The present work is located in this wide framework, proposing a procedure for seismic fragility estimation of the most recurrent masonry building typologies in historical centres on a regional scale. The methodology introduces, as a key step, a preliminary recognition about features of historical centres and related built fabric, by using multiple information sources directly implemented and integrated in GIS environment. This is aimed to define a proper taxonomy for historical centre macro-classes, according to which all the municipalities of a regional territory can be classified. At the same time, it has been possible to define a regional abacus of recurring masonry building typologies, linked with the historical centre macro-classes of the taxonomy, by using the CARTIS form compiled for some municipalities in the regional territory. Such an association allows to estimate the distribution of masonry building typologies of the whole regional territory. Therefore, a sample of models, representative of each of the most recurrent masonry building typologies, have been obtained and uncertainty was accounted by all the possible combinations of the numerical values within the ranges of some parameters selected among those contained in the abacus. For each model, numerical modelling and analysis have been performed and the results have been statistically processed to derive typological fragility curves. The methodology has been applied to the case study of Puglia region, resulting a procedure rapidly implementable on the basis of few information and easily extendable to other context of applications.

2 GENERAL FRAMEWORK: TYPOLOGICAL-MECHANICAL SEISMIC FRAGILITY FOR HISTORICAL CENTRES MACRO-CLASSES

The proposed framework is structured according two subsequent steps (Figure 1), starting from the study about morpho-typological and structural characteristics of historical centres and building fabric at regional scale, coming to the derivation of fragility curves based on a typological-mechanical approach.

The preliminary key phase, aimed to the definition of historical centres macro-classes (HC-mc) and the identification of related recurrent masonry building typologies, is made by managing and integrating several data sources with different level of detail directly in GIS environment. Knowledge gained through this initial step is composed by morpho-typological, geometrical and structural information organized in two parallel schemes: a taxonomy of HC-mc and an abacus of the most recurrent masonry building typologies. These two information structures are then matched between them, by using information collected in CARTIS forms [32] as explained in section 2.1. Then, the structural modelling and analysis have been implemented based on a typological-mechanical approach for sets of models representative of the building stock investigated and typological fragility curves have been derived through Multiple Stripe Analysis (MSA) method [17] for the recurrent masonry building typologies, within the most widespread historical centre macro-classis identified on the regional territory. The two different phases of the methodology are presented in detail in the following sections.

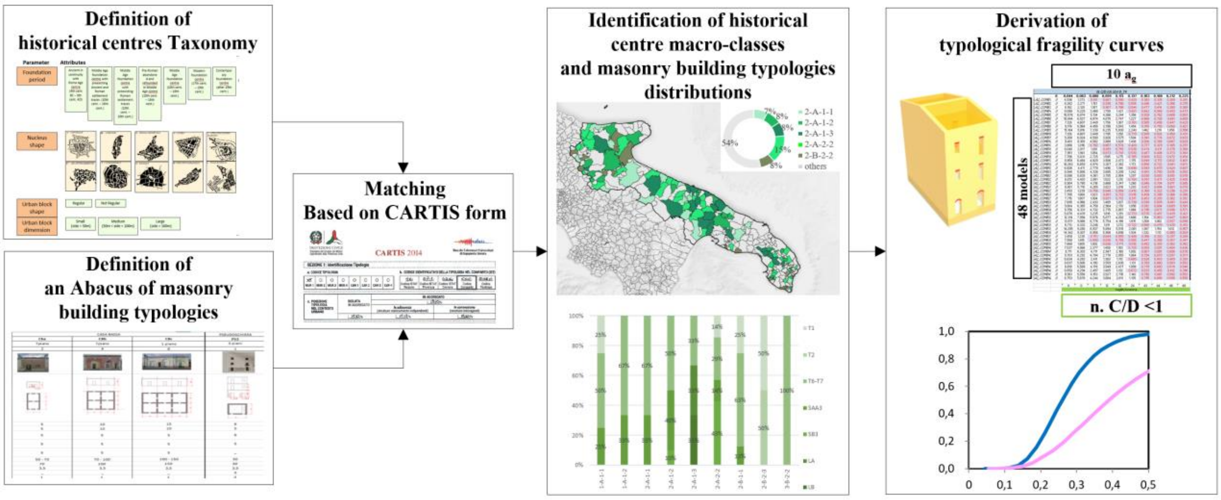


Figure 1: General framework of the methodology.

2.1 Definition of historical centres macro-classes and related masonry building typologies

The implementation of the proposed procedure starts form the study and analysis of the main characteristics of oldest nucleus of cities and their building fabric with a dual objective: (a) definition of HC-mcs; (b) identification of recurrent masonry building typologies, both standardized by means of a proper taxonomy for a fast classification of historical built heritage by means of rapid visual survey.

The HC-mcs have been characterized trough a limited number of features with corresponding attributes, as reported in Table 1. The first parameter, P_1, is the *foundation period*, for which, at prelaminar stage, 5 possible attributes have been defined. The second parameter, P_2, is the *nucleus shape* representative of the morphology of the historical centres, for which 10 related attributes have been derived from available studies and applications [6,7]. The last two parameters, P_3 and P_4, take into account the typical configuration of the building fabric within historical centres, where almost all the masonry buildings are organized in aggregates and characterized considering the regularity in plan (regular, not regular) and the length of the main plan directions (small, medium, large). In the first instance, 300 HC-mcs have been obtained as all the possible combinations of the attributes of each parameter, but such a large number would generate a very complex taxonomy hardly applicable on large scale. For this reason, it is advantageous to merge some attributes, in order to reduce the number of HC-mcs and to streamline the structure of the taxonomy. Therefore, 5 attributes of the parameter P_1 have been grouped in 4, and 10 attributes of the parameter P_2 have been groped in 3, obtaining a taxonomy composed by 72 historical HC-mcs. The obtained taxonomy allows to derive a classification of a certain historical centre, on the basis of the knowledge of limited characteristics observed or derived from rapid surveys, as extracted by multiple information layers overlapped and integrated in GIS environment.

The study for the definition of the historical centres taxonomy is useful, at the same time, for the investigation about the recurrent features of masonry building stock and the subsequent definition of a synthetic abacus of masonry building typologies. In this perspective, it is possible to rely on well-established schemes and rules available in literature to define archetypes of buildings and derive related geometrical, typological and structural features from various information catalogues and rapid visual surveys. For the aim of the present work, after the identification of the archetypes representative of the entire building stock under investigation, some related features have been extrapolated from rapid visual investigation or CARTIS catalogue, and data have been organized in few significant parameters with corresponding possible attributes or ranges of numerical values. On the basis of historical centres taxonomy and abacus of masonry building typologies, it is possible to perform a dual operation: a rapid identification and classification of oldest nucleus of the municipalities within the HC-mcs and process the related percentage distribution of masonry building typology. This last operation is possible by exploiting CARTIS form, which identifies homogeneous urban sectors and related typological-structural building classes. This means that, starting from the hypothesis that the historical centre coincides with oldest homogeneous urban sector, for the municipalities already surveyed with CARTIS form, it is possible to associate CARTIS building classes with archetypes of the abacus, by matching some geometrical features. The result is a directed association among a certain HC-mc and some building typologies from the abacus and, as a consequence, knowing the distribution of HC-mcs on a regional territory, it is possible to deduce the most recurrent masonry building typologies.

Parameter	Attributes	Aggregate Attributes
P_1 Foundation period	$P_{1,1}$ Pre Roman Age (until half 8th cent. BC) $P_{1,2}$ Roman Age (from half 8th cent. to 7th cent. AD) $P_{1,3}$ Middle Age (7th cent. – 15th cent.) $P_{1,4}$ Modern foundation (16th cent. – 19th cent.) $P_{1,5}$ Contemporary foundation (since 19th cent.)	$P_{1,1}$ Ancient foundation (until 7th cent. AD) $P_{1,2}$ Medieval foundation (7th cent. – 15th cent.) $P_{1,3}$ Modern foundation (16th cent. – 19th cent.) $P_{1,4}$ Contemporary foundation (after 19th)
P_2 Nucleus shape	$P_{2,1}$ Centralized $P_{2,2}$ Middle Age maze $P_{2,3}$ Concentric $P_{2,4}$ Radial $P_{2,5}$ In-boundaries development $P_{2,6}$ Winding $P_{2,7}$ Linear $P_{2,8}$ Parallel development $P_{2,9}$ Open $P_{2,10}$ Multiple cores	$P_{2,1}$ Centralized $P_{2,1}$ Linear $P_{2,1}$ Open
P_3 Urban block in plan regularity	$P_{3,1}$ Not regular $P_{3,2}$ Regular	$P_{3,1}$ Not regular $P_{3,2}$ Regular
P_4 Urban block dimension	$P_{4,1}$ Small $P_{4,2}$ Medium $P_{4,3}$ Large	$P_{4,1}$1. Small $P_{4,2}$ Medium $P_{4,3}$ Large

Table 1: Parameters and related attributes of HC-mcs.

2.2 Typological-mechanical approach for derivation of fragility curves

The derivation of seismic fragility curves is based on a typological-mechanical approach which involves the construction of a sample of models for each archetype obtained as all the possible combinations of related parameters contained in the abacus. Numerical modelling and analysis are implemented in the software POR2000 [33], which is based on the hypotheses of box-like behavior, shear-type scheme (constrained rotations at the base and the top sections of masonry piers), rigid roto-translation in the plan of storey slab and assuming a bilinear perfectly elasto-plastic behavior of the masonry piers. For each model, a nonlinear static analysis is implemented in two main horizontal directions (0°, 90°) and for two different horizontal load patterns: uniform (proportional to the mass) and inverse triangular (proportional to the height). After, C/D ratios are computed in terms of displacement, with reference to the life-safety (LS) limit state, which is achieved when the first pier suffers a displacement equal to 75% of near-collapse limit-state displacement for ductile mechanism, $d_{NC,D}$. This latter is assumed equal to 0.010 times the height of the panel. Fragility curves of each archetype are constructed as suggested by Baker [17], implementing nonlinear static analyses for increasing levels of PGA. The value of C/D ratios are computed for all the models of each sample, considering that the LS is exceeded when C/D is lower than 1. The fragility curves have been obtained by fitting the ratio between failures (models with C/D lower than 1) and the total number of models investigated for each PGA level, by employing the maximum likelihood method to compute median (θ) and dispersion (β) of a fragility function.

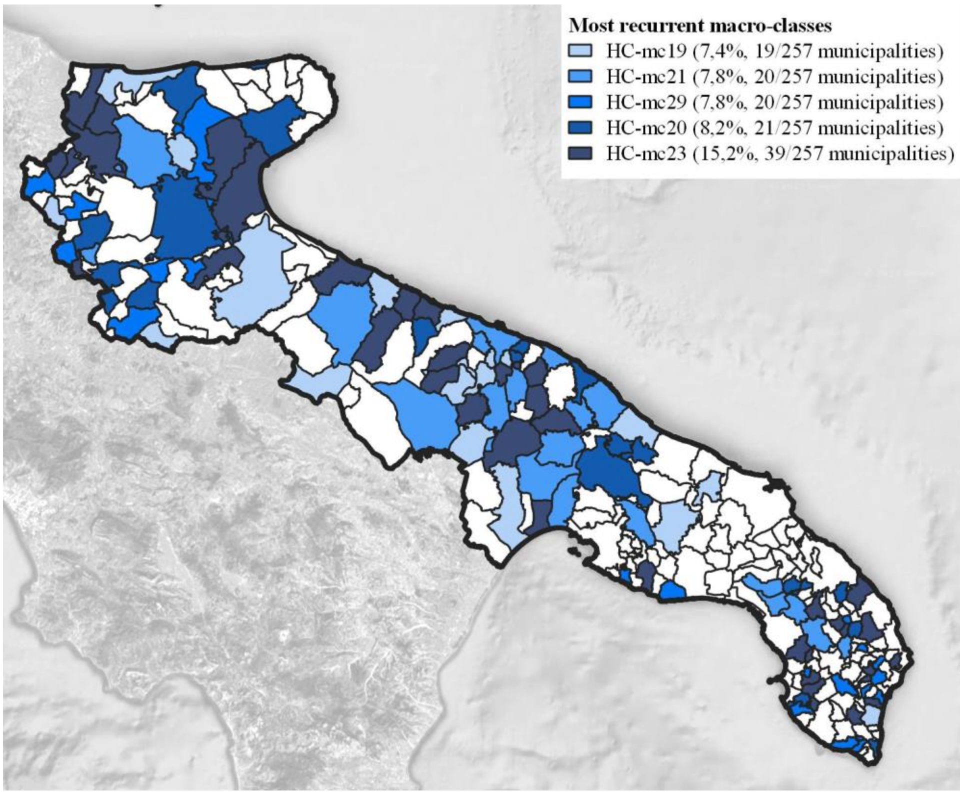
3 APPLICATION OF PROPOSED PROCEDURE: THE CASE STUDY OF PUGLIA REGION

3.1 Regional historical centres macro-classes and recurrent masonry building typologies

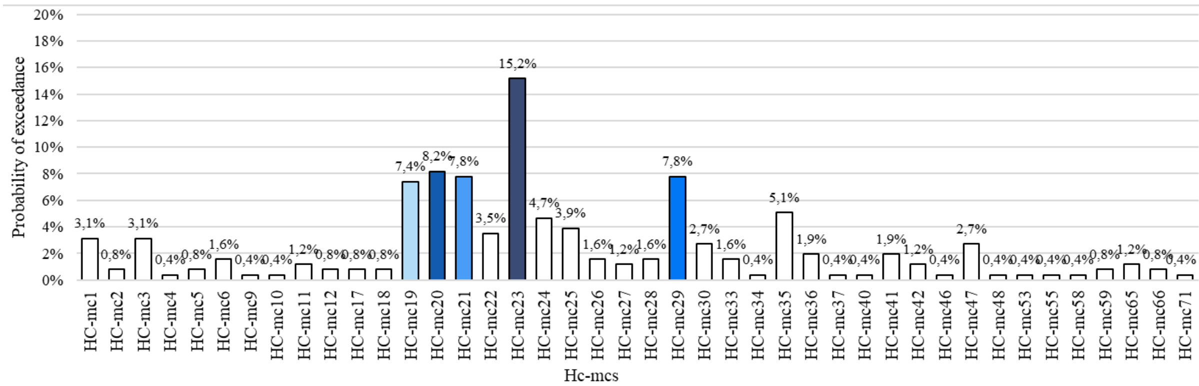
The proposed methodology was developed with reference to the case study of Puglia region.

The historical centres taxonomy was built starting from the observation and analysis of several information sources implemented in GIS environment. The starting point is the analysis of the ISTAT dataset [34], largely used for large scale investigations, giving a georeferenced shape file with administrative boundaries of each municipality and several related attributes. Hence, using this dataset, it is possible to perform a first general recognition about the number of municipalities within the investigated area, which results equal to 257. The subsequent step is the investigation about the parameter P_1, which is a feature not easily deducible from rapid visual survey, and for this reason it was useful to involve additional sources. In this context, it was opted for the use of the thematic map of Regional Landscape Plans (PPTR), freely available online on the web platform of Territorial Information System (SIT) of Puglia Region as shape files and directly implementable in GIS environment. This map reports 11 sub-regional areas characterized by homogeneity in terms of historical, morphological, and economic points of view. In the specific case, the historical development of settlements built along the entire Region was focused. Data about foundation period is extrapolated from this dataset and associated to polygons representative of each municipality.

Information about parameter P_2 is obtained by means of extensive visual inspections based on satellite orthophotos, by surveying morphology of the ancient nucleus of the cities and spatial relationship between empty spaces, such as squares and roads, and built area. Contextually, it is possible investigate the built fabric typically composed by masonry building organized in aggregate configuration, in order to derive information about the parameters P_3 and P_4. This analysis was rapidly carried out in GIS environment for the entire regional territory, managing a fast classification of the historical centres of all the 257 municipalities that fall under 42 of the total 72 HC-mcs reported in the taxonomy, as graphically shown in Figure 2.



(a)



(b)

Figure 2: a) distribution of HC-mcs on the territory of the Puglia region; b) percentage distribution of HC-mcs of the Puglia region

Within the context of the same knowledge path, it is possible to investigate the peculiar characteristics of the built fabric, aimed to the identification of recurrent masonry building typologies and the subsequent construction of a proper abacus. However, with regard to this latter, it worth pointing out that, its definition is strictly connected to the context of application. In the specific case, the investigation at regional scale has led to identify 12 masonry building typologies, represented by a proper archetype within the abacus. Each of this archetype is characterized by means of geometrical, morphological, structural. and mechanical parameters, for which plausible attributes have been derived from directly observations, measurements, or derived from and CARTIS forms, being available for 14 municipalities of Puglia region. The abacus and the parameters with related attributes are summarized in Table 2. At this point, it is possible a direct association between some HC-mcs of the municipalities surveyed with CARTIS procedure and masonry building typologies of the abacus, in the hypothesis that historical centre is coincident with the oldest homogeneous urban sector. As a consequence, it is possible to associate the 27 CARTIS masonry structural-typological classes with some masonry building typologies of the abacus, by matching range of values of geometrical parameters P_2 and P_3 from the abacus with the corresponding ones from CARTIS catalogue. The results, summarized in Table 3, show that in many cases it is not possible a one-by-one correspondence, but more than one typology of the abacus are associated to a single CARTIS typology. Nevertheless, it is possible to observe a significant recurrence of the typologies *"casa a schiera"*, indicated as SA2, SA3, SAA3, which can be considered as the most representative of built fabric of historical centres.

Masonry Building Typology	P_1 dimensions in plan (m)	P_2 mean area floor (m^2)	P_3 number of floors	P_4 interstorey height (m)	P_5 thickness of wall (m)	P_6 masonry type	P_7 percentage of opening (%)
Cba	5 m x10 m	50	1	3,5	50-25 80-50 100-50	Tuff Masonry	Ground floor 10%-20% Upper floors (if present) 20%-30%
CBb	10 m x 10 m	100	1				
CBc	15 m x 10 m	150	1				
SA2	6 m x 12 m	72	2				
SA3	6 m x 12 m	72	3				
SAA3	6 m x 12 m	72	3				
SB2	10 m x 12 m	120	2				
SB3	10 m x 12 m	120	3				
LA2	16 m x 12 m	192	2				
LA3	16 m x 12 m	192	3				
LB2	16 m x 12 m	192	2				
PA3	26 m x 16 m	413	3				

Table 2: Abacus of masonry building typologies of the Puglia region

Historical center class	CARTIS municipalities code	CARTIS building class	Abacus typologies	Occurrence of abacus typologies
HC-mc1	BOVINO	MUR1	SA2; Cba	CBa = 20% SA2 = 40% SA3 = 20% SAA3 = 20%
		MUR2	SA2; SA3; SAA3	
HC-mc2	RUVO DI PUGLIA	MUR1	SA2	SA2 = 50% SA3 = 25% SAA3 = 25%
		MUR2	SA2; SA3; SAA3	
HC-mc19	CASTELLANETA	MUR1	SA3; SAA3	SA3 = 67% SAA3 = 33%
		MUR2	SA3	
HC-mc20	CISTERNINO	MUR1	SA3; SAA3	SA2 = 25% SA3 = 33% SAA3 = 33% SB3 = 9%
		MUR2	SA3; SAA3	
	FOGGIA	MUR1	SA2	
		MUR2	SB3	
	LOCOROTONDO	MUR1	SA2; SA3; SAA3	
		MUR2	SA2; SA3; SAA3	
HC-mc21	ANDRIA	MUR1	SA2	SA2 = 33% LA2 = 33% LA3 = 33%
		MUR2	LA2; LA3; LB2	

HC-mc23	BISCEGLIE	MUR1	SA2; SA; SAA3	CBa = 10% SA2 = 20% SA3 = 10% SAA3 = 10% SB2 = 20% SB3 = 30%
		MUR2	SB2; SB3	
	FAETO	MUR1	SA2; CBa	
	SANT'AGATA DI PUGLIA	MUR1	SB3	
		MUR2	SB2; SB3	
HC-mc25	MINERVINO MURGE	MUR1	SA2	CBa = 20% SA2 = 50% SA3 = 20% SAA3 = 10%
		MUR2	SA2	
	VICO DEL GARGANO	MUR1	SA2	
		MUR2	SA2; CBa	
		MUR3	SA2; SA3; SAA3	
HC-mc30	ERCHIE	MUR1	CBb	CBa = 67% CBb = 33%
		MUR2	Cba; CBb	
HCmc37	CARLANTINO	MUR1	SA2; CBa	CBa = 50% SA2 = 50%

Table 3: Matching between HC-mcs of taxonomy and masonry building typologies of the based on CARTIS form

3.2 Derivation of typological-mechanical based fragility curves

In the light of the results of the first phase of the procedure, the seismic fragility curves have been derived for the masonry building typologies SA2, SA3, SAA3, resulting the most widespread on regional territory and, therefore, representative of a large portion of region historical built heritage. According to the mechanical-typological approach illustrated in the section 3.2, for each of these typologies a set of models have been obtained by fixing the geometrical parameters P_1, P_2, P_3, P_4, and accounting for the uncertainty related to the parameters P_5, P_6, P_7. It worth pointing out that for the parameter P_7, three value pairs of mean compressive and tensile strengths reported in Italian Building Code [35] have been considered, coherently with the observed masonry type.

For each typology, a set of 48 numerical models have been realized and analyzed by means of nonlinear static analyses. These latter have been performed in the two main horizontal directions, 0° and 90°, and using the two horizontal load patterns, uniform and inverse triangular. The intensity measure (IM) has been varied according to different levels of PGA, in order to evaluate seismic behavior at increasing intensity. For each IM level, C/D ratios lower than one have been computed, considered as the ones exceeding the LS limit state. Reporting the collapsed values to the total number of models, a proper fitting for each direction and horizontal distribution load has been performed, obtaining 4 fragility curves for each typology. Fragility curve with higher probability of exceedance has been accounted for each typology, and in all the cases, it was the one obtained by employing the inverse triangular horizontal distribution load in the 0° direction. In Table 4 the values of median θ and dispersion β for the fragility curves are reported, as well as they are illustrated in Figure 3.

Masonry building typology	θ median	β dispersion
SA2	0,1704	0,0875
SA3	0,0742	0,3226
SAA3	0,1962	0,3170

Table 4: Summary of median and dispersion for the fragility curves of the most recurring building typologies

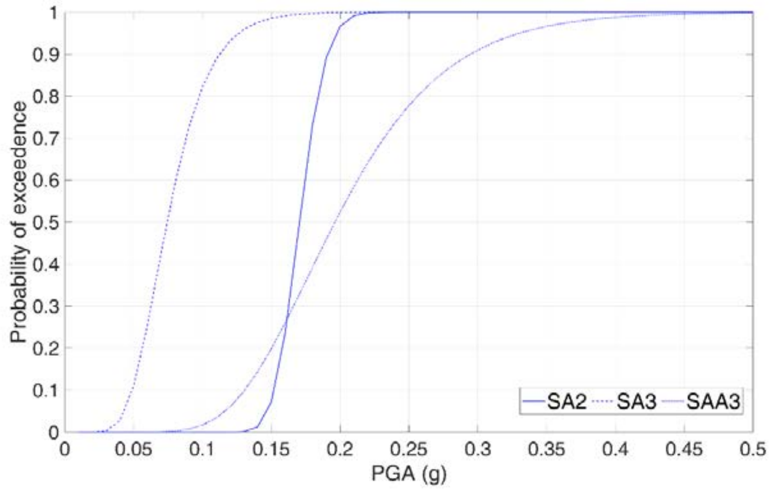


Figure 3: Seismic typological fragility curves for with reference to LS limit state of the most recurrent building typologies

4 CONCLUSIONS

The paper proposes a typological-mechanical approach to assess large-scale seismic fragility of masonry buildings in historical centres. The general framework is structured according to two subsequent phases, starting from a preliminary investigation at regional scale of historical built heritage, exploiting different information sources implemented and integrated in GIS environment. The aim of this step is the definition of a proper taxonomy of historical centre macro-classes and an abacus of masonry building typologies matched by means of CARTIS form, available for some municipalities. This operation allows to obtain information about the presence and distribution of the building typologies of the abacus within the regional territory. Then, considering the most recurrent typologies, a typological-mechanical approach was implemented, taking into account the uncertainties about geometrical and mechanical characteristics by varying related numerical values to construct sets of models representative of each typologies. For each model, a nonlinear static analysis was performed by increasing PGA and computing C/D ratios in terms of displacements. Then, a typological fragility curve has been derived, in order to describe the seismic vulnerability of a large portion of historical built heritage.

The methodology was applied to the case of study of the Puglia region, for which it was possible a rapid classification of historical centres of all the municipalities and the identification of the most recurrent masonry building typologies of the abacus. Therefore, the assessment of seismic fragility of these typologies allows to describe the current state of a large portion of historical built heritage of the regional territory.

The application shows that the methodology is easily implementable at regional scale on the basis of rapid visual survey and using few information sources. Moreover, it is worth highlighting that historical centre taxonomy obtained within the present framework can be representative of all the historical centres in the Italian context. However, the abacus of masonry building typologies is inevitably strictly connected to the context of application but represents a full scheme easily declinable for other regional contexts. A further advantage is represented by the possibility to investigate the presence and distribution of building typologies at territorial scale, on the basis of few information useful for purpose of fragility curves derivation, which can describe in a synthetic way the seismic vulnerability of large portion of historical building heritage.

The work represents a starting point of further developments; indeed, it will be possible to implement automated procedure able to enrich and infer useful information on the basis of rapid visual detections at regional scale, making more efficient the preliminary phase of the procedure. In addition, it will be possible to use of the information about morphology of urban block contained in the taxonomy to introduce and analyse the influence of aggregate configuration on fragility curves.

ACKNOWLEDGEMENTS

This work was supported by the Italian Presidency of the Council of Minister, Civil Protection Department under the project CARTIS, WP2.

The second author thanks for the support of the European Union, NextGenerationEU - National Recovery and Resilience Plan, Mission 4 Education and Research - Component 2 from research to business - Investment 1.5, ECS_00000041 VITALITY - Innovation, digitalisation and sustainability for the diffused economy in Central Italy.

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