Towards an Integrated Vulnerability Assessment of the existing building stock at the urban scale: combination of multi-source data, appraisal of the energy and seismic performance

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Towards an Integrated Vulnerability Assessment of the existing building stock at the urban scale: combination of multi-source data, appraisal of the energy and seismic performance and development of typological-mechanical models for building aggregates

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LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

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ed essendo stato ammesso a sostenere l'esame finale con la prevista discussione della tesi dal titolo:
Inglese: **Towards an Integrated Vulnerability Assessment of the existing building stock at the urban scale: combination of multi-source data, appraisal of the energy and seismic performance and development of typological-mechanical models for building aggregates**
Italiano: **Verso una valutazione integrata del patrimonio edilizio esistente: integrazione di dati multi-sorgente, stima delle prestazionali sismiche ed energetiche e sviluppo di modelli tipologico-meccanici per edifici in aggregato**

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Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica

Valeria Leggieri

Verso una Valutazione Integrata del patrimonio edilizio esistente: integrazione di dati multi-sorgente, stima delle prestazionali sismiche ed energetiche e sviluppo di modelli tipologico-meccanici per edifici in aggregato

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EXTENDED ABSTRACT (eng)

In the last few years, the seismic and energy performance assessment methodologies of existing building stock have become a central topic in ongoing research.

One of the most important issues is the considerable complexity of the evaluation of the existing buildings compared to the new design due to the uncertainties inherent the process of knowledge of the effective characteristics the buildings and the several variables involved. Moreover, the seismic events of the last few years together with the short-term objectives imposed by European Union for the improvement of energy efficiency have brought to light the urgent need of assessing the actual performance levels to plan and realize suitable retrofitting interventions. This implies the necessity to perform large-scale surveys for a huge number of buildings for which it is not possible to use the procedures generally employed to assess single buildings, due to the detailed information required and the considerable computational burden.

For this reasons, at large scale it is required the use of simplified procedures, easily implementable on the basis of limited information and able to provide results with acceptable reliability and accuracy, optimizing the cost and time connected to the process of realization of an inventory of building characteristics and subsequent implementation of the assessment procedures.

In this framework, the objective of the present research work is to provide an innovative approach for the assessment of the existing buildings in a context of uncertainty and incomplete information typical of the large scale analysis by means of a properly knowledge path to realize a suitable base of information finalized to the implementation of simplified assessment procedures.

The starting point is the construction of a geo-referenced multi sources database (GMSD) of the current residential buildings stock in GIS environment through the extraction, integration and elaboration of data from different sources. The information, collected, catalogued, and implemented in GMSD database, is structured according three level of GIS entities: census section (CS), urban block (UB), and single building (SB), to which a "standard" set of minimum data has been associated. Subsequently, the georeferenced database has been supplemented by more detailed information

extracted by “CARTIS” catalogue, containing information about the typological and structural features of homogenous urban districts, to refine the data and to obtain more detailed information associated to each building. The alphanumeric format of data allows the automatic implementation of indirect methods with a low computational effort, which provide a qualitative seismic vulnerability index at different scales (whole urban district, an urban block, a single building), the results have been compared to verify the reliability and accuracy of the data set and stored in the GMSD database together with all the information. Successively, a powerful 3D interactive tool has been realized for the knowledge, characterization and analysis at the urban scale. Two Applications have been developed for case studies in Puglia, Italy: the cities of Taranto and Bisceglie for which GMSD has been constructed and implement a rapid seismic vulnerability assessment respectively of 12674 urban blocks and 3726 single buildings.

The information available in GMSD allows to perform several types of assessment at large scale for a large set of existing buildings, in particular two methodologies have been proposed; the first, allows a large scale assessment of masonry building aggregates; the second, regard the integration of the two aspect of seismic vulnerability and energy performance of existing building stock.

A typological-mechanical approach has been elaborated and tested to assess the seismic behaviour of the masonry buildings and aggregates at large scale. The information of the different structural-typological building classes stored in GMSD database have been used to perform a statistical sampling of the existing building stock, automatically elaborating the numerical models and analyses by means of a computer code with low computational effort. The aim is to identify a simplified relations and rules to predict the seismic behaviour of masonry buildings aggregates starting from the limited information about the single building.

The second proposal is finalized to implementation of an integrated simplified evaluation procedure of the seismic vulnerability and energy performance at urban scale, two aspects generally treated in a disconnected way, ignoring the advantages and benefits that could result from an integrated strategy.

The integrate procedure is based the data collected in GMSD database complemented by a further information about building envelope and plant system feature, obtained by available technical documentations, photographic record, expeditious inspections and survey. The proposed algorithm provides the calculation of a seismic vulnerability (IV_S) and an energy performance (IV_E) index for each building by means of suitable procedure in which, for each of the two aspects, a proper set of characteristic parameters have been selected and appraised. The two indices are normalized to obtain two consistent values and combined in a synthetic integrated index (IV_I). The approach has been applied to a neighbourhood in the historical centre of Foggia obtaining in a rapid way an integrated assessment of a sample composed by 148 buildings.
On the bases of the proposed procedures it is possible to elaborate a preliminary analysis of the current state of the existing building stock in order to identify the criticality performance levels, elaborate different scenarios and plan more detailed analyses and future interventions, optimizing the available resources.

key words *Existing building stock, Regional scale, Geographic Information System, Seismic vulnerability, Energy performance, Typological-mechanical approach, Masonry building aggregates, Integrated assessment*

EXTENDED ABSTRACT (ita)

Negli ultimi anni, le metodologie di valutazione di prestazioni sismiche ed energetiche del patrimonio edilizio esistente sono diventate un tema centrale della ricerca tecnico-scientifica.

Una delle principali criticità riguarda la notevole complessità legata alle valutazioni degli edifici esistenti rispetto alla nuova progettazione dovuta alle incertezze connesse al percorso di conoscenza delle effettive caratteristiche degli edifici e alle numerose variabili coinvolte. Inoltre, gli eventi sismici degli ultimi anni e gli obiettivi di breve termine imposti dall'Unione Europea per il miglioramento dell'efficienza energetica, hanno fatto emergere l'urgenza di valutare gli attuali livelli prestazionale per pianificare e attuare adeguati interventi di miglioramento e adeguamento. Questo implica la necessità di eseguire analisi a larga scala per un enorme numero di edifici per i quali non è possibile l'uso delle procedure generalmente impiegate per valutare il singolo edificio a causa del livello di dettaglio di informazioni richieste e del considerevole onere computazionale.

Per questa ragione, a larga scala è necessario utilizzare procedure semplificate, facilmente implementabili sulla base di informazioni limitate e in grado di fornire risultati con affidabilità e accuratezza accettabile, ottimizzando costi e tempi connessi ai processi di realizzazione di archivi di informazioni e di implementazione di procedure di valutazione.

In questo quadro, l'obiettivo del presente lavoro di ricerca è quello di fornire un approccio innovativo alla valutazione degli edifici esistenti in un contesto di incertezza e informazioni limitate, tipico delle analisi a larga scala, per mezzo di un adeguato percorso di conoscenza finalizzato alla realizzazione di una opportuna base di informazioni finalizzato all'implementazione di procedure semplificati di valutazione.

Il punto di partenza è la costruzione di un database multi-sorgente georeferenziato (GMSD) del patrimonio edilizio residenziale corrente in ambiente GIS mediante estrazione, integrazione ed elaborazione di dati ricavati da diverse fonti.

Le informazioni raccolte, catalogate ed implementate in ambiente nel GMSD, sono strutturate secondo tre livelli di dettaglio: le sezioni di censimento (CS), i blocchi urbani

(UB), i singoli edifici (SB) ai quali viene associato un insieme di informazioni "standard". Successivamente, il database GMSD viene integrato con informazioni di maggior dettaglio estrapolate dal catalogo "CARTIS", contenente informazioni sulle caratteristiche tipologico-strutturali di comparti urbani omogenei, in maniera da affinare i dati e ottenere informazioni dettagliate associate a ciascun edificio. Il formato alfanumerico dei dati consente l'implementazione automatica, con un limitato onere computazionale, di metodi indiretti che forniscono un indice di vulnerabilità sismica di carattere qualitativo a scala differente (intero comparto urbano, sezione di censimento, blocco urbano, edificio singolo), i risultati vengono comparati per verificare l'affidabilità e l'accuratezza dei dati e collocati con le altre informazioni nel database GMSD. Vengono proposte due diverse applicazioni sviluppate per casi studi localizzati in Puglia: la città di Taranto e la città di Bisceglie per le quali è stato costruito il database GMSD ed è stata implementata una rapida procedura di valutazione di vulnerabilità sismica rispettivamente 12674 blocchi urbani e 3726 edifici.

Le informazioni disponibili nel database GMSD consentono l'esecuzione di differenti tipologie di valutazioni a larga scala per grandi insiemi di edifici esistenti, nello specifico, vengono proposte due metodologie: la prima, permette una valutazione a larga scala di edifici in muratura in aggregato; la seconda, riguarda l'integrazione dei due aspetti di vulnerabilità sismica e prestazioni energetiche del patrimonio edilizio esistente.

È stato elaborato e testato un approccio tipologico-meccanico per la valutazione del comportamento sismico di edifici in muratura in aggregato a larga scala. Le informazioni delle diverse classi tipologico-strutturali di edifici presenti nel database GMSD vengono utilizzate per eseguire un campionamento statistico del patrimonio edilizio esistente, implementando in maniera automatica la modellazione e l'analisi numerica tramite l'utilizzo di un codice informatico con un basso onere computazionale. Lo scopo è identificare relazioni e regole semplificate per prevedere il comportamento sismico e strutturale di un aggregato in muratura a partire dalla conoscenza di informazioni di base del singolo edificio componente.

La seconda proposta è finalizzata all'implementazione di una procedura semplificata di valutazione integrata delle prestazioni sismiche ed energetiche a scala urbana, due

aspetti generalmente trattati in maniera separata, ignorando i vantaggi e i benefici che potrebbero derivare da una strategia integrata.
La procedura integrata si basa sui dati contenuti nel database GMSD integrata da ulteriori informazioni riguardanti l'involucro dell'edificio e le caratteristiche impiantistiche ottenuta da documentazione tecnica, fotografica, ispezioni e indagini speditive.
L'algoritmo proposto prevede il calcolo di due indici di vulnerabilità sismica (IV_S) e prestazione energetica (IV_E) per ciascun edificio utilizzando opportune procedure nelle quali, per ciascuno dei due aspetti, opportuni parametri caratteristici vengono selezionati e valutati. I due indici vengono normalizzati in maniera tale da avere due grandezze coerenti e combinati in un indice sintetico integrato (IV_I). l'approccio è stato applicato ad un quartiere del centro storico di Foggia ottenendo in maniera rapida una valutazione integrata per un campione di 148 edifici.
Sulla base delle procedure proposte è possibile elaborare un'analisi preliminare dello stato corrente del patrimonio edilizio esistente in maniera da identificare livelli prestazionali critici, elaborare differenti scenari e pianificare analisi più dettagliate e futuri interventi, ottimizzando le risorse disponibili.

key words *Patrimonio edilizio esistente, Scala regionale, Geographic Information System, Vulnerabilità sismica, Prestazioni energetiche, Approccio tipologico-meccanico, Aggregati di edifici in muratura, Valutazione integrata*

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INTRODUCTION

In recent years, there has been a growing attention at the issues of seismic vulnerability mitigation and reduction of the energy consumption for existing buildings (Dolce *et al.*, 2003; Park, Hwang and Oh, 2018).

Often, the interventions on the existing buildings stock aimed at improving the seismic and energy behaviour, are designed in a disconnected way, ignoring the advantages and benefits that could result from an integrated strategy (Calvi, Sousa and Ruggeri, 2016).

In Italy, large part of the territory is characterized by a relevant seismic hazard and high vulnerability of the existing buildings (La Greca and Margani, 2018), which are also responsible of about 60% of the total energy demand of the civil sector in particular of space heating, cooling and warm water needs (Ascione *et al.*, 2013). This situation is the direct consequence of the average age of the building stock: in fact, more than 70% of the existing constructions was designed without following any seismic prescription and energy requirement (ISTAT, 2011).

Within this framework, the presence of a huge number of buildings for which it is necessary to recover a performance level adequate to the current standards requires, first of all, the development of "rapid" methods for the assessment of seismic vulnerability and energy performance suitable for the application at a large scale, and with a use of limited resources and time (Vona *et al.*, 2017). Methods of analysis at the level of the individual buildings are widely available in the literature, well developed and established. Anyway, they require very detailed data and considerable computational efforts, and, therefore, are unsuitable for a large-scale application over a wide territory in large-scale analyses.

The procedure for the seismic vulnerability assessment at large scale have been widely developed in the last 30 years (Calvi et al., 2006); indirect empirical procedures combine evaluation of few parameters (geographical position, general characteristics of the structure, possible damage), to obtain a final seismic vulnerability index by means of which to establish a relation between the seismic action and response of the buildings (Benedetti and Petrini, 1984; Lagomarsino and Giovinazzi, 2006; Perrone et al., 2015;

Zuccaro and Cacace, 2015; Uva et al., 2016; Uva, Sangiorgio, et al., 2019). Other approches aim at identifying building categories on the basis of recurrent typological and structural features and define the corrisponding vulnerability functions (Cosenza et al 2005; Del Gaudio et al 2015; Uva, Ciampoli at al 2019).

The methods for the large-scale assessment of seismic vulnerability are well established and widely used, but it is not the same for energy performance assessment. The standard methods available in the literature for energy assessment have been developed for application to individual buildings and require very detailed knowledge about the characteristics of the building envelope and installations. Different proposals of Urban Building Energy Models (UBEM) have been proposed for the application to the urban context (Torabi et al. 2018), but the framework remains still under development because, only in the last few years, the attention to the issue of energy performance are growing and consequently application of the regulatory requirement regard only the buildings of recent construction, while, for the most of existing building stock it is no possible to find data about energy behavior; moreover, the data connected to the energy consumption is often inaccessible due to privacy issue.

With regards to the relationship between seismic vulnerability and energy performance assessment, this is becoming a central topic in the current scientific research, but still very few studies are available in the literature and the approaches used are very different (Calvi, Sousa and Ruggeri, 2016; Belleri and Marini, 2016; Park, Hwang and Oh, 2018; Mosalam *et al.*, 2018; Liu *et al.*, 2019).

In all the previously mentioned methodologies, the main problem remains the uncertainty related to the availability and reliability of information on buildings together with the many additional variables that influence seismic vulnerability, energy performance and their interaction (Uva, Iannone and Leggieri, 2019). Furthermore, the accuracy and reliability of the results of assessment methods is strongly influenced by the quantity and quality of available data (Ascione *et al.*, 2013).

For this reason, it is required a suitable tool able to extract, integrate and elaborate large amount of different types of information on the bases of which to implement these type of procedures (Uva *et al.*, 2016).

The integration of data mining methodologies, GIS technology together with rapid in situ fieldwork constitutes a suitable approach to structure the information on the bases of which implemented easily and quickly methods for seismic vulnerability assessment end energy performance at large scale (Liu *et al.*, 2019). Indeed, in GIS environment, it can be possible collected several features and attributes from different sources allowing to produce combine geospatial database of building as a graphical unit linked to relative information (Matassoni *et al.*, 2013). This process allows to implemented automatic numerical algorithms for different purposes, such as multiple searches, visualisation of general information and results by zones, vulnerability assessment, damage and loss estimation (Vicente *et al.*, 2011).

In this framework, the aim of the present research work, it is proposed a procedure to extract, integrate and elaborate data from different available sources, that able to construct a geo-referenced cartographic and descriptive database in a GIS environment by means of which curry out deeper and integrated spatial analysis at large scale managing huge amount of information, as well as enabling the rapid research and suitable visualisation of data and results (Barbat *et al.*, 2010). Then, on the basis of this georeferenced database, automatically implement simplified procedures to assess at urban or wider scale, the existing building stock, in order to obtain a preliminary screening of the current state of the existing building stock.

The integration of information is curry out with subsequently association between a different minimum entity following a decreasing level of detail, taking into account that the availability and quality of information is often linked to the context of analysis (Cajot *et al.*, 2017), for this reason, the fundamental data source is represented by ISTAT datasets, the integration with other data sources allows to perform a subsequent properly disaggregation of data. Generally, it is possible to find georeferenced datasets with different level of information such as regional thematic cartography or cadastral maps. The information obtained by the integration of this datasets can be completed with those derived by catalogue of data, which, regards the typological and structural features of single buildings or typological classes of buildings, such as “CARTIS” form (Zuccaro *et al.*, 2016) obtaining a georeferenced multi-sources database (GMSD).

On the bases of the GMSD database, some applications of the simplified empiric seismic vulnerability assessment available in literature (Giovinazzi & Lagomarsino, 2001; Frassine & Giovinazzi, 2004) have been proposed performing the seismic vulnerability assessment for 12674 urban block Taranto and 3726 buildings of Bisceglie.
It is worth noting that this is only an example of the potentiality of the platform, which could be equipped with any algorithm for the indirect vulnerability assessment based on the data provided by the procedure.
Indeed, a typological-mechanical procedure for the seismic assessment of masonry building aggregates has been elaborated and tested on a pilot exemplum, the Municipality of Foggia, using the GMSD database. The information collected allows to perform a statistical sampling for different typology of masonry buildings and the identification of the typical aggregate configurations in same town compartments. The procedure is able to automatically generate numerical models of the sample by mean of proper computer code elaborated in MATLAB program language. Indeed, according with the available information, some geometrical characteristics and mechanical parameters are varied within predefined ranges, obtaining several numerical combinations with relative numerical models, nonlinear analyses are performed according to the pushover approach and it is analysed the relations between structural and seismic behaviour of the single buildings and the entire aggregates, in order to define simplified rules to predict the structural and seismic behaviour of the masonry aggregates on the base of limited knowledge of the single component building.
Finally, considering the aspect of energy performances, a further procedure is proposed for the integrated assessment of seismic vulnerability and energy performance of existing buildings at the urban scale. The methodology is implemented using the GMSD database complemented with data about building envelope and plant system derived by technical documentation, rapid survey or assumed from literature and standard coherently with the age of construction. A seismic vulnerability index IV_S and energy performance index IV_E are separately computed using suitable simplified procedures available in literature (Uva et al., 2016; Ascione et al., 2013). The two index are normalized in order to have a consistent value and combined in an synthetic index IV_I by means of

coefficient which take into account the constraints imposed by energy aspects and the invasiveness of seismic retrofit interventions. The procedure has been applied to a neighbourhood of municipality of Foggia for a sample of 148 masonry buildings.

All the results obtained by implementing the abovementioned procedures are then located, together with all the information, in GMSD database on the basis of which a 3D interactive tool have been realized for the search, elaboration and visualization of data and results.

PART I. GENERAL FRAMEWORK AND LITERATURE REVIEW

2 Building Inventory methods for the assessment of the existing buildings

2.1 Overview

The assessments of existing buildings at national, regional and urban scale are of fundamental importance for decision-makers and planner of the territory and for the management of the economic resources implemented for mitigation measures (Zuccaro, Cacace and De Gregorio, 2012).

In this context, the construction of a building inventory is necessary for the evaluation of different typology of impact scenarios at the large scale. Building inventory, generally, represents the distribution of building vulnerability classes and can be performed at different levels of detail, depending on the size of the building stock, the territorial unit of analysis and the adopted assessment model (Polese, Gaetani d'Aragona and Prota, 2019).

Despite it is object of study in the last fifty years, this theme together with the availability and accessibility of data sources at large scale, remains still an open issue (Zuccaro, Cacace and De Gregorio, 2012); indeed, with the aim to overcome this obstacle, several procedures continue to be proposed in literature.

In the framework of seismic vulnerability assessments, the simpler procedures classify buildings according the material of the lateral load resisting system (Grünthal, 1998). However, the vulnerability models can be significantly enhanced if additional information on relevant building characteristics are considered such as construction age, number of storeys or the type of horizontal system (Braga et al., 1982; Lagomarsino & Giovinazzi, 2006). Consequently, the proper classification within a buildings inventory could become a burdensome step in terms of time cost (Polese, Gaetani d'Aragona and Prota, 2019).

In the present chapter it is proposed a thorough review of the recent advancement in the context of the data collection techniques and the existing buildings inventories at territorial scale.

2.2 Building inventory procedures and data sources at different scales

The main purpose of the building classification is to group buildings in categories that show comparable overall performances (Lang *et al.*, 2018), this implies the knowledge of the morpho-typological characteristics with a level of detail connected to the scope of the evaluation.

H. Lang et al 2018 and Polese et al. 2019 (Lang *et al.*, 2018; Polese, Gaetani d'Aragona and Prota, 2019) propose an exhaustive appraisal of the various approaches to the data collection and building inventories techniques available in the recent literature, listed in Table 2.2.1 (Polese, Gaetani d'Aragona and Prota, 2019), considering the different scale of applicability, ranging from global (Jaiswal & Wald, 2008; Brzev et al., 2013; Pitilakis *et al.*, 2014) to more specific classifications (FEMA, 2003; Lagomarsino & Giovinazzi, 2006). It is clear that, the scale of applicability is strictly connected to the typology of data, available resource and aim of the evaluation and the more the information about the buildings is complete, the more accurate assessment will result, with subsequently more reliable evaluation of the seismic response (Maio et al., 2018).

Detailed investigations at level of single building, as required by current standard, are very burdensome, time and costly consuming for the large-scale applications. Indeed, the need of building classification schemes stems from the fact that it is impossible to consider each building with its individual structural and non-structural features for an area or region with a great number of individual buildings. The grouping of the buildings into a certain number of structural typological classes represents a compromise useful to a more manageable and efficient study maintaining tan acceptable reliability of the results (Lang et al., 2018). Another fundamental reason is to define a common terminology or taxonomy in order to represent in uniform way variations in building design and construction practices around the world (Brzev et al., 2013).

The availability of procedure for large scale applications developed in the last five decades (Calvi *et al.*, 2006) and well established in particular in the seismic vulnerability and risk assessments field, allows the use of several type of datasets with a different level of detail. In the framework of the large scale applications, the needs to use different type of information at different scale implies an adequate planning and design of the investigations and knowledge path to calibrate the available resources and requires properly tools, able to collect huge amount of data with a level of detail suitable to the scale of the analysis and on the bases of which to obtain a reliable evaluation.

Table 2.2.1 - Data sources and related approaches for building inventory (Polese, Gaetani d'Aragona and Prota, 2019)

Source	Building features	Applicability scale	Advantage	Disadvantage	Example applications for inventory
Census data	Spatial type features - basilar level (storey number) Attribute type features - basilar level (age; material - RC/Masonry/Other; state of preservation)	from town districts to regional or national scale	complete database for all the nation; information on both population and buildings; free or low-cost database	some countries have limited info by census returns; variable size of census unit; data are available in aggregated form at the census tract level for privacy reason; census forms compiled by non-experts	(Meroni *et al.*, 2017) (Zuccaro, Cacace and De Gregorio, 2012) (Crowley *et al.*, 2012)
Remote sensing (HR or VHR imagery)	Spatial type features - intermediate level (building shape, position and height)	from town districts to regional, national or even larger scale	automatic and semi-automatic detection algorithms are being developed; georeferenced spread data on potentially very large building stock; can be easily updated	requires processing massive data volumes; necessary the combination with other data sources (e.g. urban context information and/or local surveys on benchmark buildings) to derive attribute type building features (e.g. construction age, roof type)	(Miura and Midorikawa, 2006) (Polli, Dell'Acqua and Gamba, 2009) (Freire *et al.*, 2010)
Interview based survey	Detailed spatial and attribute type building features for building typologies and % incidence of building typologies in a district	from town districts to regional or national scale	detailed info for building typologies; speed economic approach	data reliability depends on interviewed experience/knowledge of the built environment	(Guéguen, Michel and Lecorre, 2007) (Dolce, Zuccaro and Papa, 2002)
Building by building	Detailed spatial and attribute type building features	town districts	detailed info for single buildings in a district	costly and time consuming; difficulty of access to information for not visible features (e.g. horizontal system; strengthening interventions etc.)	(Del Gaudio *et al.*, 2015) (Polese, Di Ludovico and Prota, 2018)

2.2.1 Building inventory procedures based on general and typological data

The building inventory procedures based on general data are applied at a very wide scale, ranging from global to national level. The aim of this procedures is to obtain a general buildings macro-classification on the bases of the main parameter that affect the building's behaviour such as structural system, result of the combination of the construction material and the load-bearing structure, geometric configuration-based criteria (in terms of height range and footprint area) and level of code design and age of construction.

The major international building classification schemes and relative criteria, developed in the last decades, are listed in Table 2.2.2. (Lang *et al.*, 2018); the common aim is the attempt to define all possible construction typologies on the bases of few data (generally available at national level) in order to be usable in any application context.

Table 2.2.2 - Overview of major building classification schemes considering structural system and geometric configuration (Lang *et al.*, 2018)

Name (Reference)	Regional Applicability	No. of typology classes	(Wall) Construction material	Load-bearing structure	Heigh Range	Level of code design
ATC-13 (ATC, 1985)	U.S.	40 typologies over 17 building classes	✓	✓	✓	-
PSI (Spence, *et al,* 1992)	Global	Worldwide typologies	✓	✓	-	-
RISK–UE (Lungu *et al.* 2001; (Milutinovic and Trendafiloski, 2003)	Europe	65 typologies over 23 building classes	✓	✓	✓	-
WHE (www.world-housing.net)	Global	45 subtypes over 14 load-bearing typologies	✓	✓	-	-
HAZUS–MH (FEMA, 2003)	U.S.	36 model building types over 15 building classes	✓	✓	✓	✓
UN–Habitat (UN Habitat 2007)	Global	20wall type classes	✓	-	-	-
PAGER (Jaiswal and Wald 2008)	Global	20 wall type classes	✓	✓	✓	-
GEM (Brzev *et al.* 2012)	Global	13 attributes re defined, Associated with specific building characteristics	✓	✓	✓	✓

Table 2.2.2 - Overview of major building classification schemes considering structural system and geometric configuration (Lang *et al.*, 2018)

Name (Reference)	Regional Applicability	No. of typology classes	(Wall) Construction material	Load-bearing structure	Heigh Range	Level of code design
SYNER-G Taxonomy (Hancilar and Taucer 2013)	Europe	32 main categories and 44 sub-categories	✓	✓	✓	✓
EMCA Building Typology (Wieland *et al.* 2015)	Central Asia	16 subtypes over 6 material/load-bearing classes	✓	✓	(✓)	(✓)

One of the first example of building classification scheme is the Medvedev-Sponheuer-Karnik scale (MSK–64) (Medvedev, Sponheuer and Karnik, 1965). In the MSK–64 scale, buildings were initially classified according to their material as well as type of load-bearing system into three distinct vulnerability classes A, B and C. Later, the classification scheme of MSK-64 evolved in the European Macroseismic Scale EMS (Grünthal, 1998) and complemented by three more classes D, E and F in order to account for more structural materials (e.g. structural steel) as well as various levels of earthquake-resistant design. The different Vulnerability Classes assigned to the various structural types following EMS-98 and MSK-64 are compared in Table 2.2.3.

In HAZUS 1999 (NIBS, 1999), a building classification was defined to estimate damage to buildings and lifelines. In this report general building stock represents typical buildings of a given model building type designed to withstand either High-Code, Moderate-Code or Low-Code seismic standards, or not seismically designed (referred to as Pre-Code buildings). Buildings are classified both in terms of their structural system or model building type and in terms of their use or occupancy class. In the model building type definition the structural system is considered as the key factor to assess the overall building performance, loss of function and casualties. 36 model building types are used to classify buildings within the overall categories of wood, steel, concrete, masonry and mobile listed in Table 2.2.4. Hence model building type is a function of the building height. The buildings are described as low-rise (LR), moderate-rise (MR) and high-rise (HR) (Elnashai and Erberik, 2003).

Table 2.2.3 - Overview of major building classification schemes considering structural system and geometric configuration (Lang *et al.*, 2018)

Material	Type of structure	MSK-64[2]	EMS-98
Masonry	Rubble stone, fieldstone	A	A
	Adobe (earth brick)	A	A (–B)
	Simple stone	A	(A--) B
	Massive stone	B	(B–) C (--D)
	Unreinforced, with manufactured stone units	B	(A--) B (--C)
	Unreinforced, with RC floor	B	(B–) C (--D)
	Reinforced or confined	(C)[3]	(C--) D (– E)
Reinforced Concrete (RC)	Frame without ERD[1]	C	(A--) (B–) C (--D)
	Frame with moderate level of ERD[1]		(B--) (C–) D (–E)
	Frame with high level of ERD[1]		(C--) (D–) E (–F)
	Wall without ERD[1]		(B--) C (–D)
	Wall with moderate level of ERD[1]		(C--) D (–E)
	Wall with high level of ERD[1]		(D--) E (–F)
Steel	Steel structure	-	(C--) (D–) E (–F)
Wood	Timber structure	B - C[4]	(B--) (C–) D (–E)

[1]ERD: Earthquake resistant design

[2]A – most likely, (---) less probable range, (—) probable range of Vulnerability Class

[3]building typology was not yet defined

[4]if well-built, Vulnerability Class C shall be assigned

Table 2.2.4 - HAZUS Model Building Types (Elnashai and Erberik, 2003)

No	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1	W1	Wood, light frame (<5000 sq.ft.)		All	1	14
2	W2	Wood (>5000 sq.ft.)		All	2	24
3	S1L	Steel Moment Frame	LR	1-3	2	24
4	S1M		MR	4-7	5	60
5	S1H		HR	8+	13	156
6	S2L	Steel Braced Frame	LR	1-3	2	24
7	S2M		MR	4-7	5	60
8	S1H		HR	8+	13	156
9	S3	Steel Light Frame		All	1	15

Table 2.2.4 - HAZUS Model Building Types (Elnashai and Erberik, 2003)

No	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	LR	1-3	2	24
11	S4M		MR	4-7	5	60
12	S4H		HR	8+	13	156
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	LR	1-3	2	24
14	S5M		MR	4-7	5	60
15	S5H		HR	8+	13	156
16	C1L	Concrete Moment Frame	LR	1-3	2	20
17	C1M		MR	4-7	5	50
18	C1H		HR	8+	12	120
19	C2L	Concrete Shear Walls	LR	1-3	2	20
20	C2M		MR	4-7	5	50
21	C2H		HR	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	LR	1-3	2	20
23	C3M		MR	4-7	5	50
24	C3H		HR	8+	12	120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26	PC2L	Precast Concrete Frame with Concrete Shear Walls	LR	1-3	2	20
27	PC2M		MR	4-7	5	50
28	PC2H		HR	8+	12	120
29	RM1L	Reinforced Masonry Bearing Walls /w Wood or Metal Deck Diaphragms	LR	1-3	2	20
30	RM1M		MR	4+	5	50
31	RM2L	Reinforced Masonry Bearing Walls /w Precast Concrete Diaphragms	LR	1-3	2	20
32	RM2M		MR	4-7	5	50
33	RM2H		HR	8+	12	120
34	URML	Unreinforced Masonry Bearing Walls	LR	1-2	1	15
35	URMM		MR	3+	3	39
36	MH	Mobile Homes		All	1	12

The RISK-UE (Mouroux *et al.*, 2004) projects analyse the vulnerability of the buildings requiring only the age of construction and general information about the building typology. In this framework, the analyses of the most recurrent different building types in all European and Mediterranean countries has been performed, proposing a matrix (BTM) of 23 building types (Table 2.2.5), to group together structures that would be expected to behave similarly during a seismic event, essentially corresponds to that adopted by EMS-98 (Grünthal, 1998).

Table 2.2.5 - Matrix of Masonry and RC typology of selected structured European buildings, (Mouroux *et al.*, 2004)

Lebel	Description of type	Lebel	Description of type
M	**Masonry structures**	**RC**	**Reinforced concrete structure**
M1	Load-bearing masonry walls composed of:	RC1	Support beams/columns
1.1	*rubble*	RC2	Structural concrete wall
1.2	*freestone*	RC3	Support beams / columns with unreinforced brick-lined wall:
1.3	*Ashlar*	3.1	*Even brick-lined structures*
M2	Crue	3.2	*Uneven structures (i.e., uneven support beams, uneven brick lining, flexible level)*
M3	Load-bearing unreinforced masonry walls:	RC4	Compound structure of reinforced concrete (portico and concrete walls)
3.1	*Hardwood flooring*	RC5	Prefabricated concrete walls
3.2	*Masonry arches*	RC6	Prefabricated concrete walls with structural concrete walls
3.3	*Floors with metal and masonry joists*		
3.4	*Reinforced concrete floors*		
M4	Load-bearing reinforced masonry walls		
M5	Structures made completely of reinforced masonry		

In the Crowley 2012 (Crowley *et al.*, 2012) the aim was to develop a European building inventory database to feed into the Global Exposure Database initiative of the Global Earthquake Model (GEM). The main sources of building stock information being collected for each country are national building or dwelling censuses and national records on construction practices performed by statistical or financial services of the country. The main steps in the development of the European Building Inventory database include the identification of all the available data sources in the various European countries; the development of a method to infer building counts from other data sources such as dwelling counts in the absence of building data; the production of preliminary algorithms to assess building structural typology characteristics from the available data; the expert elicitation to check and further develop sub-national building typology distributions in each country. The key objectives of this project are the development of a database that describes the number and area of different European building typologies within each cell of a grid, with a resolution of at least 30 arc seconds (approximately 1km square at the equator) for use in the seismic risk assessment of European buildings. The statistical significance of the data within each grid cell will vary from administrative level 0 (i.e. country-based) down to administrative level 5 (the highest sub-national boundary level). A quality rating will also need to be assigned to the data, varying according to the resolution and source of the data. The focus is on residential buildings, and then the inclusion of non-commercial buildings within the database will be considered.

The GEM Building Taxonomy (Brzev *et al.*, 2013) describes and classifies the buildings in a uniform manner as a key step towards assessing their seismic risk. Criteria for development of the GEM Building Taxonomy were that the Taxonomy be relevant to seismic performance of different construction types. The Taxonomy was developed in conjunction with other GEM researchers and builds on the knowledge base from other taxonomies, including the EERI and IAEE World Housing Encyclopedia, PAGER-STR, and HAZUS.

The Taxonomy is organized as a series of expandable tables, which contain information pertaining to various building attributes, each attribute describes a specific characteristic of an individual building or a class of buildings that could potentially affect their seismic performance. The following 13 attributes have been included in the last GEM Building Taxonomy Version 2.0:

1. Direction;
2. Material of the lateral load-resisting system;
3. Lateral load-resisting system;
4. Height;
5. Date of construction of retrofit;
6. Occupancy;
7. Building position within a block;
8. Shape of the building plan;
9. Structural irregularity;
10. Exterior walls;
11. Roof;
12. Floor;
13. Foundation system.

Each attribute describes a specific characteristic of an individual building or a class of buildings that could potentially affect their seismic performance.

In Italy, an interesting methodology of building inventory at national level was developed by the Zuccaro at al 2012 (Zuccaro, Cacace and De Gregorio, 2012) able to furnish a seismic vulnerability assessment on the basis of “poor” information collected by the Italian Census (2001) of population and buildings (DB_Census). In particular, the statistic relations, linking this information of general type to the vulnerability classes (A, B, C, D) commonly adopted in macro seismic analysis, have been determined. This has been possible thanks to the examination of “specific” information on structural typologies (DB_Plinivs) contained in a wide sample of buildings spread out in all the Italian territory and investigated by a quick building by building survey promoted by PLINIVS Study Centre. This procedure is structured according to the following steps:

1. Identification of six descriptive characteristics common to the two Data Bases (DB_Census and DB_Plinivs): building position in the aggregate, material of

vertical structure, age of building, number of floors above ground, altimetry and demographic class.

2. Statistical analysis of the relations between the descriptive characteristics and the vulnerability classes of the surveyed buildings (DB_Plinivs).
3. Application of the correlations to Census data and assessment of the vulnerability class distribution for each Italian municipality.
4. Check of the distributions with reference to the surveyed data for census section.
5. Application of the calibration procedures and assessment of the vulnerability distributions at regional or national scale.

This method has been then refined (Cacace *et al.*, 2018) with the proposal of BINC procedure, allowing a generalization of buildings distribution on the vulnerability classes at regional national scale. The methodology can be easily extended to all countries having census data on buildings.

In Polese et al, 2019 building inventory is built in probabilistic terms, using census (ISTAT) and Cartis databases to evaluate the central values of probability distributions for selected parameters, and a first comparison of the results in terms of building inventory and the subsequent impact assessment are performed.

2.2.2 Expert judgment and form survey procedures

The interview-based and form survey procedures are classified as a second level approach requiring extensive and more detailed data which have to be collected on the base of an expert judgment of specialised technicians by means of rapid in situ survey evaluating the observed condition of the building.

In the framework of these procedure, a fundamental method is represent by GNDT form (GNDT, 1993) developed by the National Group for Defence against Earthquake (GNDT, Gruppo Nazionale per la Difesa dai Terremoti). The 1st level GNDT form required general data about location, geometry, use, age of construction, structural typology and maintenance and damage state (Figure 2.2.1).

Two type of 2nd level GNDT forms are proposed respectively for Masonry and Reinforced Concrete buildings. For the Masonry buildings (Figure 2.2.2), data is collected with regarding to the following 11 parameters:

1. Type and organization of the resisting system;
2. Quality of the resisting system;
3. Conventional strength;
4. Building position and foundations;
5. Horizontal diaphragms;
6. Plan configuration;
7. Height configuration;
8. Maximum distance between walls;
9. Roof;
10. Non-structural elements;
11. General maintenance conditions.

Instead, for the reinforced concrete buildings (Figure 2.2.3), data is collected regarding only the following 4 parameters:

1. Type and organization of the resisting system;
2. Distribution of infill panels;
3. Planimetric configuration;
4. In eight irregularity.

Each parameter can be classified from A–D in order from better to worst condition and as it contributes to an increasing vulnerability of the building, moreover, for each parameter it is required a score about quality of information.

GRUPPO NAZIONALE PER LA DIFESA DAI TERREMOTI (G.N.D.T.) – C.N.R.
Scheda di 1° livello per il rilevamento dell'esposizione e della vulnerabilità degli edifici

GNDT

Sezione 1 – DATI RELATIVI ALLA SCHEDA

Codice ISTAT Provincia 1
Codice ISTAT Comune 3
Comune

Scheda n° 6
Data 11
Squadra 17
Prescheda

Sezione 2 – LOCALIZZAZIONE EDIFICIO

Codice ISTAT sezione Censuaria 19

RIFERIMENTO CATASTALE
Foglio 22 Mappale 25 Particella 28

CARTOGRAFIA DI RILEVAZIONE
Foglio 32 Aggregato strutturale 34 Edificio 38

URBANISTICA
Zona di piano 40 Piano attuativo 41 Vincoli 42

Aggregato strutturale Edificio

0 via, viale 1 corso
2 vicolo 3 piazza, largo 43
4 località

Nome 44

N° civico 56

N° accessi 60 N° fronti a comune 62

Sezione 3 – DATI METRICI

63, 68, 73, 78
Superficie media coperta (mq)
N° piani a superficie media coperta uguale

83, 86, 89, 92, 95
Altezza media interpiano (m)
N° piani ad altezza media interp. uguale

Altezza massima fuori terra valutata alla gronda (m) 98
Altezza minima fuori terra valutata alla gronda (m) 101
Larghezza stradale fronte principale (m) 104

Sezione 4 – USO

Totale unità d'uso 106

Stato dell'edificio 108
F finito
N non finito
C in costruzione

Totale unità d'uso 109
1 totalmente utilizzato
2 parzialmente utilizzato
3 non utilizzato
4 abbandonato

Proprietà 110

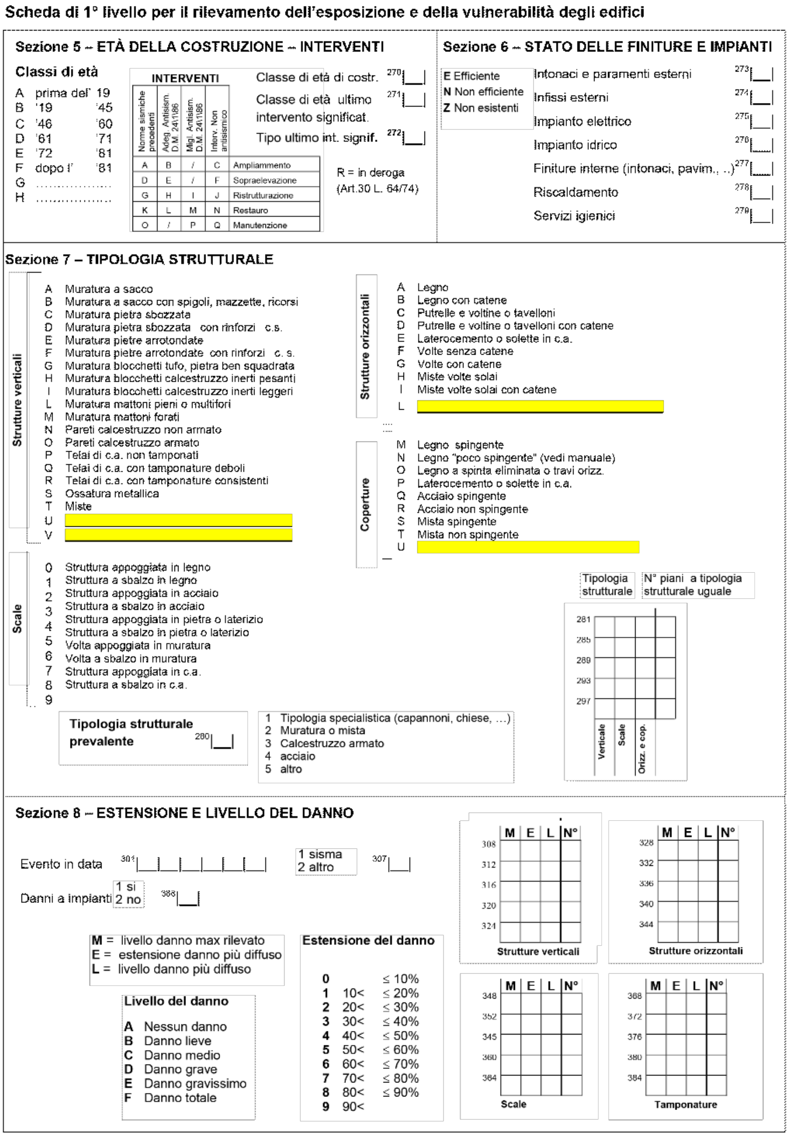
Conduzione prevalente 111
1 diretta
2 in locazione

Residenza (1 si, 2 no) 112 — Abitazioni occupate: N° 113, Sup.% 115 — Abitazioni libere: N° 116, Sup.% 118 — Abitazioni occup. salt.: N° 119, Sup.% 121

Att. produttive 122 (1 si, 2 no) Servizi pubblici 123 (1 si, 2 no) Denomin. edificio 124

Unità d'uso: N°	Codice	Tipo	Sup.%	Intensità d'uso: Periodo di utilizzazione – Mesi	giorni	Utilizzazione Potenziale – media	max	h/gg	Bacino Di utenza
138	140	143	144	145		150		157	159
160	162	165	166	167		172		179	181
182	184	187	188	189		194		201	203
204	206	209	210	211		216		223	225
226	228	231	232	233		238		245	247
248	250	253	254	255		260		267	269

Figure 2.2.1 - 1st level GNDT survey form



Scheda di 1° livello per il rilevamento dell'esposizione e della vulnerabilità degli edifici

Sezione 5 – ETÀ DELLA COSTRUZIONE – INTERVENTI

Classi di età

A prima del' 19
B '19 '45
C '46 '60
D '61 '71
E '72 '81
F dopo il '81
G ....
H ....

INTERVENTI

Norme sismiche precedenti	Adeg. Antisism. D.M. 24/1/86	Migl. Antisism. D.M. 24/1/86	Interv. Non antisismico	
A	B	/	C	Ampliammento
D	E	/	F	Sopraelevazione
G	H	I	J	Ristrutturazione
K	L	M	N	Restauro
O	/	P	Q	Manutenzione

Classe di età di costr. 270|__|
Classe di età ultimo intervento significat. 271|__|
Tipo ultimo int. signif. 272|__|

R = in deroga (Art.30 L. 64/74)

Sezione 6 – STATO DELLE FINITURE E IMPIANTI

E Efficiente
N Non efficiente
Z Non esistenti

Intonaci e paramenti esterni 273|__|
Infissi esterni 274|__|
Impianto elettrico 275|__|
Impianto idrico 276|__|
Finiture interne (intonaci, pavim., ..) 277|__|
Riscaldamento 278|__|
Servizi igienici 279|__|

Sezione 7 – TIPOLOGIA STRUTTURALE

Strutture verticali

A Muratura a sacco
B Muratura a sacco con spigoli, mazzette, ricorsi
C Muratura pietra sbozzata
D Muratura pietra sbozzata con rinforzi c.s.
E Muratura pietre arrotondate
F Muratura pietre arrotondate con rinforzi c. s.
G Muratura blocchetti tufo, pietra ben squadrata
H Muratura blocchetti calcestruzzo inerti pesanti
I Muratura blocchetti calcestruzzo inerti leggeri
L Muratura mattoni pieni o multifori
M Muratura mattoni forati
N Pareti calcestruzzo non armato
O Pareti calcestruzzo armato
P Telai di c.a. non tamponati
Q Telai di c.a. con tamponature deboli
R Telai di c.a. con tamponature consistenti
S Ossatura metallica
T Miste
U
V

Strutture orizzontali

A Legno
B Legno con catene
C Putrelle e voltine o tavelloni
D Putrelle e voltine o tavelloni con catene
E Laterocemento o solette in c.a.
F Volte senza catene
G Volte con catene
H Miste volte solai
I Miste volte solai con catene
L

Coperture

M Legno spingente
N Legno "poco spingente" (vedi manuale)
O Legno a spinta eliminata o travi orizz.
P Laterocemento o solette in c.a.
Q Acciaio spingente
R Acciaio non spingente
S Mista spingente
T Mista non spingente
U

Scale

0 Struttura appoggiata in legno
1 Struttura a sbalzo in legno
2 Struttura appoggiata in acciaio
3 Struttura a sbalzo in acciaio
4 Struttura appoggiata in pietra o laterizio
5 Struttura a sbalzo in pietra o laterizio
6 Volta appoggiata in muratura
7 Volta a sbalzo in muratura
8 Struttura appoggiata in c.a.
9 Struttura a sbalzo in c.a.

Tipologia strutturale | N° piani a tipologia strutturale uguale

281, 285, 289, 293, 297 — Verticale | Scale | Orizz. e cop.

Tipologia strutturale prevalente 280|__|

1 Tipologia specialistica (capannoni, chiese, ...)
2 Muratura o mista
3 Calcestruzzo armato
4 acciaio
5 altro

Sezione 8 – ESTENSIONE E LIVELLO DEL DANNO

Evento in data 301|__|__|__|__|__|__|

1 sisma
2 altro 307|__|

Danni a impianti 1 si 2 no 388|__|

M = livello danno max rilevato
E = estensione danno più diffuso
L = livello danno più diffuso

Livello del danno

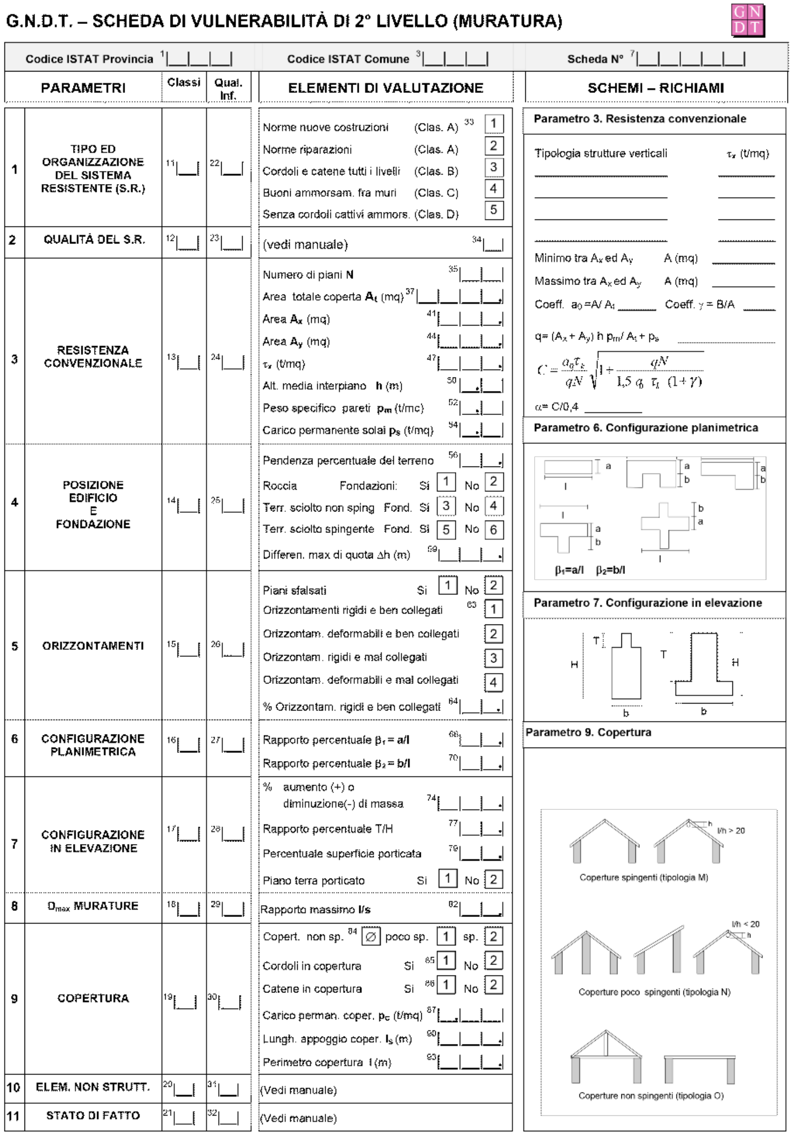
A Nessun danno
B Danno lieve
C Danno medio
D Danno grave
E Danno gravissimo
F Danno totale

Estensione del danno

0 ≤ 10%
1 10< ≤ 20%
2 20< ≤ 30%
3 30< ≤ 40%
4 40< ≤ 50%
5 50< ≤ 60%
6 60< ≤ 70%
7 70< ≤ 80%
8 80< ≤ 90%
9 90<

M | E | L | N° — 308, 312, 316, 320, 324 — Strutture verticali
M | E | L | N° — 328, 332, 336, 340, 344 — Strutture orizzontali
M | E | L | N° — 348, 352, 345, 360, 364 — Scale
M | E | L | N° — 368, 372, 376, 380, 384 — Tamponature

Figure 2.2.1 - 1st level GNDT survey form



G.N.D.T. – SCHEDA DI VULNERABILITÀ DI 2° LIVELLO (MURATURA)

GNDT

Codice ISTAT Provincia [1]			Codice ISTAT Comune [3]	Scheda N° [7]
PARAMETRI	Classi	Qual. Inf.	ELEMENTI DI VALUTAZIONE	SCHEMI – RICHIAMI
1 TIPO ED ORGANIZZAZIONE DEL SISTEMA RESISTENTE (S.R.)	11	22	Norme nuove costruzioni (Clas. A) 33 [1] Norme riparazioni (Clas. A) [2] Cordoli e catene tutti i livelli (Clas. B) [3] Buoni ammorsam. fra muri (Clas. C) [4] Senza cordoli cattivi ammors. (Clas. D) [5]	**Parametro 3. Resistenza convenzionale** Tipologia strutture verticali τ_k (t/mq)
2 QUALITÀ DEL S.R.	12	23	(vedi manuale) 34	
3 RESISTENZA CONVENZIONALE	13	24	Numero di piani **N** 35 Area totale coperta $\mathbf{A_t}$ (mq) 37 Area $\mathbf{A_x}$ (mq) 41 Area $\mathbf{A_y}$ (mq) 44 τ_k (t/mq) 47 Alt. media interpiano **h** (m) 50 Peso specifico pareti $\mathbf{p_m}$ (t/mc) 52 Carico permanente solai $\mathbf{p_s}$ (t/mq) 54	Minimo tra A_x ed A_y A (mq) Massimo tra A_x ed A_y A (mq) Coeff. $a_0 = A/A_t$ Coeff. $\gamma = B/A$ $q = (A_x + A_y)\, h\, p_m / A_t + p_s$ $C = \frac{a_0 \tau_k}{qN}\sqrt{1 + \frac{qN}{1{,}5\, a_0\, \tau_k\, (1+\gamma)}}$ $\alpha = C/0{,}4$
4 POSIZIONE EDIFICIO E FONDAZIONE	14	25	Pendenza percentuale del terreno 56 Roccia Fondazioni: Si [1] No [2] Terr. sciolto non sping Fond. Si [3] No [4] Terr. sciolto spingente Fond. Si [5] No [6] Differen. max di quota Δh (m) 59	**Parametro 6. Configurazione planimetrica** $\beta_1 = a/l$ $\beta_2 = b/l$
5 ORIZZONTAMENTI	15	26	Piani sfalsati Si [1] No [2] Orizzontamenti rigidi e ben collegati 63 [1] Orizzontam. deformabili e ben collegati [2] Orizzontam. rigidi e mal collegati [3] Orizzontam. deformabili e mal collegati [4] % Orizzontam. rigidi e ben collegati 64	**Parametro 7. Configurazione in elevazione**
6 CONFIGURAZIONE PLANIMETRICA	16	27	Rapporto percentuale $\beta_1 = a/l$ 66 Rapporto percentuale $\beta_2 = b/l$ 70	**Parametro 9. Copertura**
7 CONFIGURAZIONE IN ELEVAZIONE	17	28	% aumento (+) o diminuzione(-) di massa 74 Rapporto percentuale T/H 77 Percentuale superficie porticata 79 Piano terra porticato Si [1] No [2]	Coperture spingenti (tipologia M)
8 D_{max} MURATURE	18	29	Rapporto massimo **l/s** 82	
9 COPERTURA	19	30	Copert. non sp. 84 [∅] poco sp. [1] sp. [2] Cordoli in copertura Si 85 [1] No [2] Catene in copertura Si 86 [1] No [2] Carico perman. coper. p_c (t/mq) 87 Lungh. appoggio coper. l_s (m) 90 Perimetro copertura l (m) 93	Coperture poco spingenti (tipologia N) Coperture non spingenti (tipologia O)
10 ELEM. NON STRUTT.	20	31	(Vedi manuale)	
11 STATO DI FATTO	21	32	(Vedi manuale)	

Figure 2.2.2 - 2nd GNDT survey forms for Masonry structure

G.N.D.T. – SCHEDA DI VULNERABILITÀ DI 2° LIVELLO (CALCESTRUZZO ARMATO)

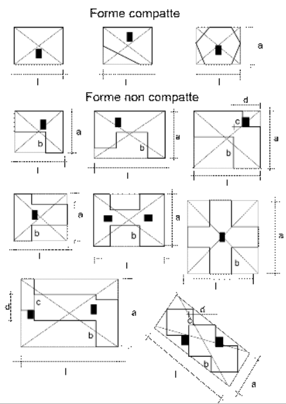
Codice ISTAT Provincia [1]|__|__|__|		Codice ISTAT Comune 4|__|__|__|	Scheda N° 7|__|__|__|__|__|
PARAMETRI	**Classi**	**ELEMENTI DI VALUTAZIONE E SCHEMI – RICHIAMI**	
1 TIPO ED ORGANIZZAZIONE DEL SISTEMA RESISTENTE	|__|	***La valutazione va riferita alla direzione più debole.*** **1** Pareti in c.a. in entrambi le direzione **2** Pilastri e travi alte **3** Pilastri e travi in spessore di solaio **4** Altro ____________ **5** Non so	
2 DISTIBUZIONE DELLE TAMPONATURE	|__|	***Considerare solo le tamponature esterne e i campi di tamponatura pieni per più del 70% a contatto con la maglia strutturale (travi e pilastri).*** **A** Su 4 lati esterni **B** Su 3 lati esterni **C** Su 2 lati esterni **D** Su 1 lato esterno	
3 CONFIGURAZIONE PLANIMETRICA	Forma |__|	***Il nucleo scale e ascensore sono da considerarsi resistenti quando sono realizzati o in pareti di c.a. o a struttura intelaiata con tamponatura consistente (Blocchi cls o tufo, mattoni pieni o forati doppio UNI)*** **1** Forma compatta con nucleo scala/ascensore resistente centrale **2** Forma compatta con nucleo scala/ascensore resistente eccentrico **3** Forma non compatta con nucleo scala ascensore resistente centrale **4** Forma non compatta con nucleo scala/ascensore resistente eccentrico	
4 IRREGOLARITA IN ELEVAZIONE	Piano debole |__| Pilastri tozzi |__|	***Per piano debole si intende un piano che ha una rigidezza ridotta rispetto agli altri come il caso di piano pilotis o piani con grandi aperture o piani privi di tamponature o tamponature poste in aggetto o arretrate rispetto alla maglia strutturale*** **A** Assente **B** Diverso dal piano terra con nucleo scala/ascensore resistente **C** Al piano terra con nucleo scala/ascensore resistente **D** Diverso dal piano terra senza nucleo scala/ascensore resistente **E** Al piano terra senza nucleo scala/ascensore resistente **1** Assenti **2** Per travi a ginocchio o piani sfalsati **3** Per finestre a nastro **4** Altro____________	

Figure 2.2.3 - 2nd GNDT survey forms for Reinforced Concrete structure

On the scheme of GNDT form other similar procedure have been proposed: In the 2016 Uva, (Uva *et al.*, 2016), it is proposed a specific survey form aimed at collection of data of masonry and reinforced concrete. Expert technicians collect information about buildings by means of rapid visual inspections, filling in the ANTAEUS vulnerability form with general data of the building and parameters which affect the seismic behaviour of the structure; actual damage of the building. One form is filled in for each independent structural unit, moreover, in the case of a structural aggregate with more units in structural continuity, position of the unit within the aggregate is taken into account as a specific parameter.
In Formisano et al 2015 (Formisano *et al.*, 2015) a revised format of survey form is developed and calibrated for the masonry building aggregate, adding five parameters to the eleven of the GNDT form for masonry buildings, accounting for the aggregate conditions among adjacent units.
Several other proposal of survey forms are proposed in literature (Monteiro *et al.*, 2016; Taffarel *et al.*, 2016; Jiménez, Pelà and Hurtado, 2018) with the common aim to allows a rapid data collection an seismic vulnerability assessment of existing building at large scale.
One of the most important and diffuse inspection procedure, particularly for post-earthquake damage and safety assessment inspection are the AeDES forms (Baggio *et al.*, 2007). AeDES form aims at surveying the typological, damage levels and usability characteristics of residential buildings, in the emergency phase following an earthquake. The forms are compiled building by building interpreted as structural units of ordinary constructional typology (typically masonry, reinforced concrete or steel, etc..). allowing a quick survey and a first identification of the building stock, with the collection of metrical and typological data of the buildings. Even if the final judgment remains a competence of the surveyor team, this form is a useful tool for the collection better computerization of data as well as evaluation of usability.
The form is the outcome of the field experience, matured after several past earthquakes, when forms with different levels of detail were used (Irpinia ’80, Abruzzo ’84, Basilicata ’90, Reggio Emilia ’96). It was a long elaboration involved a group of researchers and

experts of the National Group for the Defence against Earthquakes (GNDT) and the National Seismic Survey (SSN). The present form comes from the optimisation of the different needs of the way from the survey to the final decision (being it about usability or economical evaluation of damage), trying to avoid the collection of data which are not very significant for the scope of the survey, or which are difficult to know or unreliable. A peculiar characteristic, distinguishing the AeDES form from the other forms, concerns the typological classification of the different constructional components. The survey form is simple and this determines generally a higher reliability of the data, provided that the synthesis requested to the surveyor.

The survey form can define the position of each building, its position in the aggregate of buildings, and a geometrical description of the building such as the number of stories, average story height, average floor area, building age, building use, number of units with the respective number of occupants and percentage of utilization. The dimensional data must be reported in a variable range of values. In the survey form horizontal and vertical structural types of masonry buildings are required, but they are generally defined on the basis of only the external survey (Baggio *et al.*, 2007).

A recent advancement towards compilation of regional scale inventories is provided by the Cartis approach (Zuccaro *et al.*, 2016), implemented in Italy by Civil Protection Department in ReLUIS project. The Cartis survey form have a different approach with respect to the classical concept of survey forms, allowing the data collection about recurrent characteristics of structural-typological building classes within Town Compartments (TC). These territorial units are zones in the town that are characterized by homogeneity of the building stock in terms of construction age and construction techniques and/or structural types.

The procedure is finalized to define for each TC the relative classes of existing residential buildings on the bases of recurrent features through a data gathering in forms structured in 4 section:

Section 0: delimitation of urban sector;

Section 1: identification of prevailing buildings typology class for each urban sector;

Section 2: identification of general characteristics of each building typology class;

Section 3: characterization of the structural elements of each building typology class, closely linked to seismic behaviour of buildings in exam.

The Cartis survey form (one form for each town, comprising one or more TCs) is compiled by interviewing one or more technicians that are local experts with deep knowledge of the construction characteristics in the area. Interviewed technicians may be expert professionals (e.g. engineers or architects) having operated for years on the territory, or expert public employees in technical local administration offices. The information collected on building typologies with Cartis form are disaggregated and include data that allow to use more refined vulnerability models with respect to the ones adopting the ISTAT data. The Cartis approach exploits an original idea already proposed and preliminary experimented. Employing the Cartis approach the survey on nearly 300 municipalities in Italy has already been completed and a web application allowing the consultation of data is being implemented and tested.

2.2.3 Remote Sensing ang GIS-based approaches

Innovative techniques based on image processing are another important source for the collection of data and building inventory, allowing to rapidly gather spread geo-referenced information on building stock. "Spatial" type building features can be objectively measured from high resolution (HR) or very high resolution (VHR) optical satellite imagery, e.g. footprint shape and size, number of floors, height of floors etc. Automatic and semi-automatic procedures for data recognition are being developed (Gamba, P., Dell'Acqua, F., & Lisini, 2009) and several interesting applications based on the sole use of satellite images, or in combination with airborne radar sensors may be found, e.g. (Freire et al., 2010; Polli et al., 2009). However, "attribute" type building features, that are crucial for vulnerability assessment, such as the distinction of building materials, e.g. masonry/reinforced concrete, or the building age, cannot be easily decided relying on earth observation data alone and remote sensing methods should be combined with other sources of information to allow extraction of relevant vulnerability parameters. For example, urban context information can be used to guide automatic roof type recognition based on spectral characteristics of the visible surface materials (Mueller *et al.*, 2006). Also, HR satellite images can be used to update existing GIS building inventories based on image analyses techniques (Miura and Midorikawa, 2006).

A GIS is a digitized tool in which is possible to store, handle, elaborate, analyze, and represent spatial variables, supported by geo-referenced data. This complex architecture permits to correlate/compare different sets of data through different actions such as topologic overlay, spatial query, buffering, network analysis; often with the help of ortho-rectified imagery).
The fundamental goal of a GIS system is geo-referencing the information about geometry, topology and/or attributes, representing real world objects with digital data in a relational structure. Geometry regards shape, point, line, polygon, dimension and geographical position. Topology involves reciprocal relationships between objects. Attributes incorporate information associated to each object.
There are two broad data typologies for both abstractions: raster and vector. Raster data are grids of elementary cells called pixel units, for which the dimension depends on the datum accuracy. As example, raster data can be images, where each pixel or cell contains a colour value. Vector data are points, lines, and polygons, codified and stored according to their spatial coordinates. The relational organization of a GIS database permits to create new information layers by managing previous stored data without forced paths, following selected keywords and building different scenarios.
GIS information can be accessed, transferred, transformed, overlaid, processed and displayed using numerous software applications through a huge variety of formats. Moreover, a GIS database should be flexible, freely available for use by any country and organization through internet access, open-source, capable to be multihazard and international in scope, encouraging the worldwide community to participate to their development and validation (Indirli, 2009).
Indirli 2009 (Indirli, 2009) concerned San Giuliano di Puglia (hit by the 2002 earthquake) because a lot of material was available due to several activities performed there by ENEA experts. Architectonic/urban planning studies regarded the whole ancient core, while vulnerability analysis focused a specific inner sector. The project stressed the following points: evaluation of the impact of main natural/anthropic hazards; architectonic/urban planning and vulnerability analyses for a pilot building stock in the historic area; surveys and vulnerability evaluations on monumental churches; suggestion

guidelines for future interventions. A huge amount of information about identification, general description, architecture quality, structural condition was stored in the GIS. Different indexes have been properly elaborated and then overlapped in order to obtain further data layers. On the bases of which a SWOT analysis is curried out. The vulnerability analysis focused on a specific urban sector inside the historic centre, is performed by using Italian procedures AeDES 2000 and GNDT, and following the well-known methodology based on the analysis of collapse mechanisms. Finally, the surveys underlined the widespread existence of several damage mechanisms, until partial collapse. All the collected data and direct surveys permitted to classify accurately in the GIS platform: the building geometry in terms of plans, sections, fronts; planimetry in terms of position, elevation and foundations; materials and details such as type of masonry walls, floors and roofs; distance between the walls; mortar type; presence of external stairs and balconies, buttresses, steel ties and connections, weak points; non-structural elements; earthquake damage and maintenance. A detailed work has been dedicated to identify the abacus of the building typologies, taking into account that most of the Italian historic nuclei evolved similarly, in plan and elevation, starting from common basic cells (Giuffrè, 1993).
For all these reasons Geographic information system (GIS) represents a powerful tool to collect, integrate and menage large amount of data about the existing building stock.
In Vona et al 2017 (Vona *et al.*, 2017) the characterization of an historical centre and its buildings has been treated considering a new approach and existing common techniques for assessment of buildings dimensional characteristics. Using GIS, data collected on the investigated historical centre has been analysed to obtain the typological characterization of the surveyed buildings in order to evaluate the seismic vulnerability, urban resilience, and recovery strategies for historical centre. Based on comparison with an existing classical procedure, the approach seems to be more appropriate to carry out a first evaluation of post seismic damage.
Jiménez et al 2018 (Jiménez, Pelà and Hurtado, 2018) the Geographic Information System (GIS) is used as suitable tools to generate databases, as well as to store, analyse and manage a large amount of building information. A properly data-collection survey strategy is proposed for building stocks of urban historical centres and it is

defined a methodology for typological building survey able to collect essential information for the subsequent seismic vulnerability assessment. All the data collected during the survey activities is compiled by using GIS to create reliable databases to understand the structural characteristics of the different building typologies of the study area. Accurate databases with complete information contributes to improve the quality and reliability of the large-scale seismic vulnerability assessment. GIS allow to create unequivocal geometrical data with individual IDs, generated from digital maps or another graphical source, that are flagged with alphanumeric information. Digital data are organized in layers that are properly linked with the corresponding element's ID.
Several other applications proposed in literature (Kim *et al.*, 2020; Qiong-Lin, Zhi-Ping and Si-Yi, 2020; Zanazzi, Coïsson and Ferretti, 2019; Hansapinyo, Latcharote and Limkatanyu, 2020; Khan, 2020; Amaro-Mellado and Bui, 2020; Escobar-Wolf *et al.*, 2021) show that Remote Sensing and GIS represent suitable approaches to collect big amount of data allowing to overcome the issues of the lack of information generally connected to the large scale applications, moreover it is possible to implement with a low burden numerous typology of assessment procedures for the existing building stock.

2.2.4 Building-by-building approaches

Building-by-building surveys, represent a 3rd level approaches providing detailed data for both spatial and attribute type features for single buildings in an investigated area, are generally the most complete source towards vulnerability classification. Given the elevated costs and time, this kind of detailed survey is generally applied during post-earthquake vulnerability and damage survey campaigns (Braga, Dolce and Liberatore, 1982; Dolce *et al.*, 2003; Dolce and Goretti, 2005). Building-by-building surveys performed on selected town districts can be used as benchmark information for data mining approaches, as suggested in (Riedel *et al.*, 2014; Riedel I., Guéguen P., Dalla Mura M., Pathier E., Leduc T., 2015), or to integrate and/or verify poor data available in CE databases, as proposed in several applications.
International standards propose general framework and recommendations for these types of procedures. The current approach required a very detailed information mainly

related to geometry, construction details, and material properties of the structure and component parts. A Knowledge Level (KL) is defined as a function of the amount of information gathered to overcome the incomplete knowledge proposed in these standards, the uncertainty of information is taken into account by means of application of a Confidence Factor (CF) on specific parameter set generally regarding the mechanical characteristic of the material.

3 Simplified methods for the seismic vulnerability assessment of the existing buildings at large scale

3.1 Overview

Most of the Italian territory has a relevant seismicity and a large number of existing buildings is characterised by a high seismic vulnerability (La Greca and Margani, 2018), indeed, more than 70% of the existing real estate was made in the absence of any seismic standard (Giovinazzi and Lagomarsino, 2001). For this reason, the mitigation of seismic risk can be reached through suitable measures aimed to improve their seismic behaviour (Manfredi, 2018; Cara *et al.*, 2018).

In this framework, seismic vulnerability assessment methodologies of existing building stock at large scale have become a central topic in ongoing research (Calvi *et al.*, 2006; Belleri and Marini, 2016; De Matteis and Zizi, 2019; Pelà, 2018).

The literature on the topic (Calvi *et al.*, 2006; Dolce et al., 2020; Kassem *et al.,* 2020) defines at least three different approaches (as summed in Figure 3.1.1) to develop vulnerability models:

– Empirical/observational approaches, where the vulnerability is derived from the synthetic analysis of the formal and structural characteristics; indeed, a restricted number of building categories called "vulnerability classes" is defined as a function of the typological and structural characteristics, models are formulated on the basis of damage observed in occasion of previous earthquakes and statistically processed used to calibrate the vulnerability function for each vulnerability class;

– Mechanical/analytical approaches, where fragility is computed according to an analytical-based estimation of the buildings' response and damage estimation; the vulnerability evaluation is the result of accurate computations using techniques provided by the structural mechanics;

– Hybrid approaches, that combine different evaluation systems, e.g. expert based or analytical based assessment with subsequent empirical calibration by observational data. Hybrid damage probability matrices and vulnerability functions combine post-earthquake damage statistics with simulated, analytical damage statistics from a mathematical model of the building typology under consideration.

These are, clearly, three quite different approaches, In particular with regard to the scale of analyses. The Empirical/observational approaches present the advantage of requiring limited information and rapid processing. For this reason, it is useful for investigating a wide range of buildings at urban scale or wider, achieving a greater reliability of results while maintaining an acceptable quick investigation.

The Mechanical/analytical approaches provide a more reliable assessments on single buildings, but it requires very detailed knowledge of the features of the single buildings and the development of time-consuming structural calculations. For this reason, it is difficult the application at large scale.

Instead, hybrid models can be particularly advantageous when there is a lack of damage data at certain intensity levels for the geographical area under consideration and they also allow calibration of the analytical model to be carried out (Calvi *et al.*, 2006).

Other important classification of the seismic vulnerability methods can be defined according to their level of complexity and to the required input information:

- 1st level approaches require “poor” data regarding qualitative characteristics such building typology or age of construction, generally applicable at national, regional and urban scale;
- 2nd level approaches request more specific information about the morphological, geometrical and structural characteristic of the buildings; such methods can be applied generally at urban or district scale;
- 3rd level approaches involve a very detailed knowledge of the geometrical, structural and mechanical characteristics of the single building and their component parts, allowing a sophisticated analysis. Despite the reliability and accuracy of the results, these kind of methods imply analytical procedures that hardly applicable to large-scale assessment due to their high computational burden (Jiménez, Pelà and Hurtado, 2018).

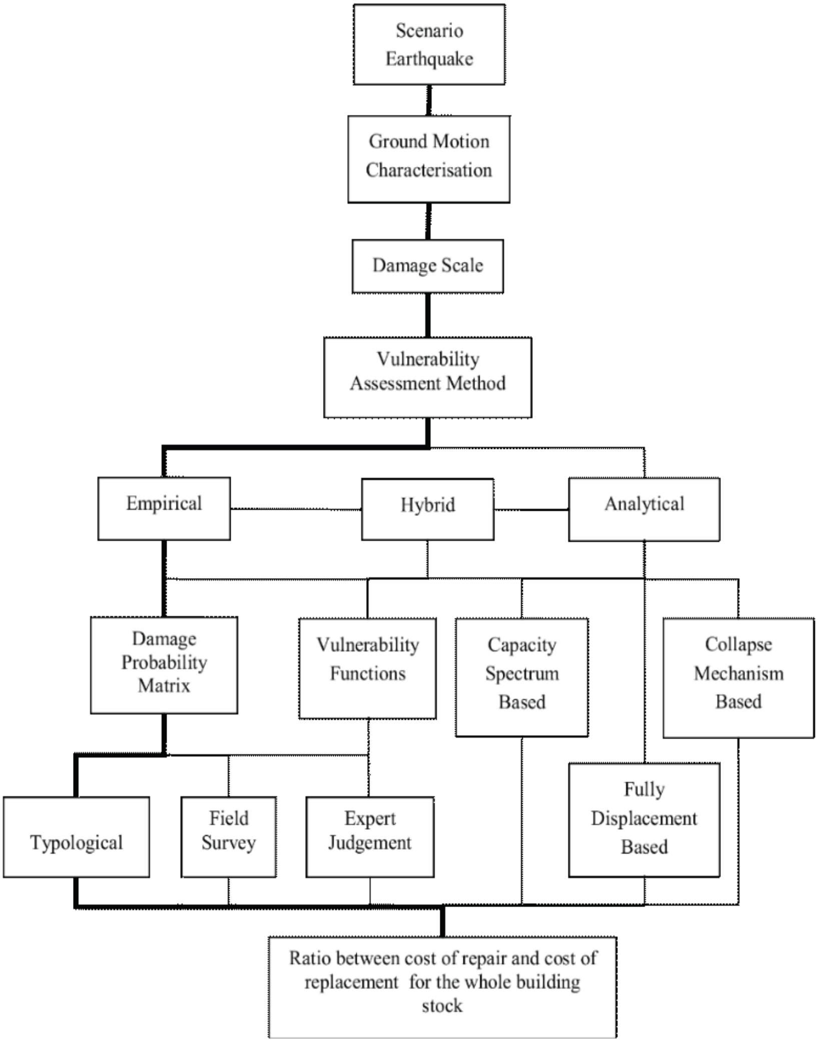


Figure 3.1.1 – The components of seismic risk assessment and choices for the vulnerability assessment procedure; the bold path shows a traditional assessment method (Calvi *et al.*, 2006)

3.2 Empirical observational approaches

The first procedures for the seismic vulnerability assessment of buildings at large scales have been developed during the early 70's, when empirical methods were proposed and calibrated as a function of macroseismic intensities. This because almost all the hazard maps were defined in terms of discrete damage scales and empirical approaches constituted the only reasonable and possible approaches usable a large scale. It is possible define two main types of empirical methods for the seismic vulnerability assessment of buildings based on the damage observed after earthquakes, both of which define damage-motion relationships:

- Damage Probability Matrices (DPM), which represent in a discrete form the conditional probability $P[D=j|i]$ to obtain a damage level j, under a ground motion of intensity i;
- Index Vulnerability Methods, in which the seismic vulnerability of a building is quantified by means of a numerical indicator;
- Continuous Vulnerability Functions, which are continuous functions expressing the probability of exceeding a given damage state, as a function of the earthquake intensity;
- Screening Methods, which allow a rapid qualitative estimation of the seismic vulnerability.

3.2.1 Damage Probability Matrices

The concept of a DPM is that a certain structural typology will have the same probability of being in a given damage state for a given earthquake intensity (Calvi *et al.*, 2006).
In this procedure the assessment of structural vulnerability is qualitative, providing the result in terms of probabilistic or deterministic percentage per damage level of buildings with the advantage represented by the need of only one parameter ranges between 0 and 1 (0% and 100%); typological, defining a building class on the basis of few general characteristics; direct, defining for a building typological class a simple relation between intensity and observed damage (Corsanego and Petrini, 1990). In a Figure 3.2.1 is shown a typical scheme of a DPM.

Earthquake Intensity	Damage Level 1	Damage Level 2	…	Damage Level n
I	…%	…%		…%
II	…%	…%		…%
I_{max}	…%	…%		…%

Figure 3.2.1 - basic scheme of a DPM

Damage Probability Matrices were first introduced in ATC-13 (ATC, 1985). More than 50 senior earthquake engineering experts provided low, best and high estimates of the damage factor as a ratio of loss to replacement cost in term of percentage for 36 different building classes according to the Modified Mercalli Intensities (MMI) from VI to XII for. The low and high damage factor estimates were defined as the 90% probability bounds of a lognormal distribution then used to calculate the probability of a central damage factor by finding the area below the curve within a given damage factor range. The result is a DPM for each intensity level for each building class (Calvi *et al.*, 2006).
A different DPMs scheme was proposed by Whitman et al. (Whitman *et al.*, 1997) to predict in probabilistic way the damage to the buildings from earthquakes. The DPMs are defined for different structural typologies according to the damaged sustained in over 1600 buildings after the 1971 San Fernando earthquake, the proportions of buildings with a given level of structural and non-structural damage are provided as a function of intensity.
One of the first version of DPMs matrix in Italian context was proposed by Braga et al. 1982 (Braga and Dolce, 1982), elaborated using the damage data of the 1980 Irpinia earthquake for which it was carried out an extensive survey campaigns evaluating the damage level of about 38.000 buildings of 41 town affected by the earthquake. The statistical elaboration of the data allowed the definition of the DPMs on the bases or the MSK scale for the recurrent building typologies of the area separated into three vulnerability classes A, B and C as showed in Figure 3.2.2. Di Pasquale et al. (Di Pasquale, Orsini and Romeo, 2005) changed these DPMs from the MSK scale to the MCS scale according the main Italian seismic catalogues, and taking into account the buildings

replaced by dwellings in order to use the results in conjunction with the 1991 Italian National Statistical Office (ISTAT) data.

Dolce et al. 2003 (Dolce *et al.*, 2003) have also adapted the original matrices as part of the ENSeRVES project (European Network on Seismic Risk, Vulnerability and Earthquake Scenarios) considering an additional vulnerability class D and using the EMS98 scale (Grünthal, 1998), to account for the buildings constructed since 1980.

A macroseismic method has been proposed by Giovinazzi and Lagomarsino (Giovinazzi and Lagomarsino, 2001; Lagomarsino and Giovinazzi, 2006) that leads to the definition of damage probability functions based on the EMS-98 macroseismic scale (Grünthal, 1998). The EMS-98 scale defines qualitative descriptions of “Few”, “Many” and “Most” for five damage grades for the levels of intensity ranging from V to XII for six different classes of decreasing vulnerability (from A to F). Damage matrices contain a qualitative description of the proportion of buildings that belong to each damage grade for various levels of intensity as shown in Figure 3.2.3.

Class A						
Intensity	**Damage level**					
	0	**1**	**2**	**3**	**4**	**5**
VI	0.188	0.373	0.296	0.117	0.023	0.002
VII	0.064	0.234	0.344	0.252	0.092	0.014
VIII	0.002	0.020	0.108	0.287	0.381	0.202
IX	0.0	0.001	0.017	0.111	0.372	0.498
X	0.0	0.0	0.002	0.030	0.234	0.734

Figure 3.2.2 - DPM constructed by Braga-Dolce-Liberatore for class A

Damage Level	Damage Grade				
Intensity	D_1	D_2	D_3	D_4	D_5
V					
VI	Few				
VII		Few			
VIII		Many	Few		
IX			Many	Few	
X				Many	Few
XI					Many
XII					Most

Figure 3.2.3 - implicit Damage Probability Matrix (DPM) for class A (Lagomarsino and Giovinazzi, 2006)

The DPMs based on intensity allow the assessment of seismic risk at large scale in efficient and cost-effective manner also because in the past seismic hazard maps were defined in terms of macroseismic intensity. Moreover, the use of observed damage data to predict the future effects of earthquakes also has the advantage that when the damage probability matrices are applied to regions with similar characteristics, it is possible to obtain a realistic indication of the expected damage inherently accounting for uncertainties. However, it worth to highlight various disadvantages associated with the use of empirical methods such as DPMs:

- A macroseismic intensity scale is defined starting from the observed damage of the building stock, this means that in a loss model both the ground motion and the vulnerability are derived on the observed damage caused by an earthquakes;
- The construction of DPMs requires the collection of post-earthquakes building damages whit reference to areas with similar ground conditions and for a several range of ground motions and this imply the statistical combination of multiple earthquake events. Moreover, few high magnitude earthquakes occur near densely populated areas and for this reason the available data tends the low damage/ground motion end this means that the statistical validity of the DPMs is limited for the high damage/ground motions.

- Seismic hazard maps are now defined in terms of PGA or spectral ordinates, thus the intensity have to be correlated to the PGA but the uncertainty in this equation is frequently ignored. In addition, when the vulnerability is defined in terms of PGA, it must be considered that often recordings of the level of the ground shaking at the site of damage are not available and it is necessary to predict the ground shaking at the site under analysis by means of properly prediction equation introducing additional uncertainty; finally, using the PGA, it is neglected the relationship between the frequency content of the ground motions and the period of vibration of the buildings

3.2.2 Vulnerability index methods

The Vulnerability Index Method (VIM) was used extensively in the past few decades and is based on a collection of a large amount of data about existing buildings; this method is defined indirect because a relationship between the seismic action and the response is established by means of a vulnerability index (Benedetti and Petrini, 1984).

In Italian context the National Group of Defence from Earthquakes (GNDT) developed an index vulnerability methodology based on a field survey form to collect information on the main parameters influencing the structural and seismic behaviour of the buildings. The survey forms are structured according two level of information:

- The 1st level GNDT form;
- The 2nd level GNDT form;

The 1st level GNDT form allow the collection of general data, as mentioned in section 2.2.2.

The 2nd level GNDT form is based on the collection of information about the main parameters of the buildings which could influence its vulnerability: for example, plan and elevation configuration, type of foundation, structural and non-structural elements, state of conservation and type and quality of materials.

The data collection in the form it is structured in 11 parameters, for which different coefficient K_i are defined according the quality from A (optimal) to D (unfavourable) with a relative weight to account for their relative importance. The global vulnerability index of each building is then evaluated using the following formula:

$$I_V = \sum_{i=1}^{11} K_i W_i \quad 3.2.1$$

The vulnerability index ranges from 0 to 382.5, but is generally normalised from 0 to 100, where 0 represents the least vulnerable buildings and 100 the most vulnerable.
The 2st level methodology is different for masonry and reinforced concrete structure, in Table 3.2.1 the cores for the masonry structure assessment are summarized.
A similar relationship was applied for RC buildings, but the main difference was in the parameters' weights assumed to be equal to 1.0. These parameters described the deficiencies and the faults of the structure depending on expert visual observations. Furthermore, a criterion to describe vulnerability classes from less vulnerable A to most vulnerable C is also proposed as shown in Table 3.2.2. A proper formula allows to transform the vulnerability index calculated for RC building in equivalent index to masonry vulnerability indices.
The data from past earthquakes is used to calibrate vulnerability functions to relate the vulnerability index I_v to a global damage factor d of buildings belonging to the same typology, for the same macroseismic intensity or PGA. The damage factor ranges between 0 and 1 and defines the ratio of repair cost to replacement cost. The damage factor is assumed negligible for PGA values less than a given threshold and it increases linearly up until a collapse PGA, from where it takes a value of 1 (Figure 3.2.4).

Table 3.2.1 - Masonry building classes and relative weight of each parameter (GNDT, 1993)

Number	Parameters	K_i Classes				Weight
		A	B	C	D	W
1	Type and organization of resisting system	0	5	20	45	1.00
2	Resistant system quality	0	5	25	45	0.25
3	Aggregate strength	0	5	25	45	1.50
4	Location and foundation of building	0	5	15	45	0.75
5	Diaphragms horizontal elements	0	5	25	45	Variable
6	Configuration of plan layout	0	5	25	45	0.50
7	Configuration in height and elevation	0	5	25	45	Variable
8	Optimum distance between walls	0	5	25	45	0.25
9	Roof	0	5	25	45	Variable
10	Non-structural elements (NS)	0	5	25	45	0.25
11	Particular terms of maintenance	0	5	25	45	1.00

Table 3.2.2 - RC building classes and relative weight of each parameter (GNDT, 1993)

Number	Parameters	Weight		
		A	B	C
1	Type and organization of resisting system	0.00	-1.00	-2.00
2	Resistant system quality	0.00	-0.25	-0.50
3	Aggregate strength	0.25	0.00	-0.25
4	Location and foundation of building	0.00	-0.25	-0.50
5	Diaphragms horizontal elements	0.00	-0.25	-0.50
6	Configuration of plan layout	0.00	-0.25	-0.50
7	Configuration in height and elevation	0.00	-0.50	-1.50
8	Critical elements connections and links	0.00	-0.25	-0.50
9	Elements of low ductility	0.00	-0.25	-0.50
10	Non-structural elements (NS)	0.00	-0.25	-0.50
11	Particular terms of maintenance	0.00	-0.50	-1.00

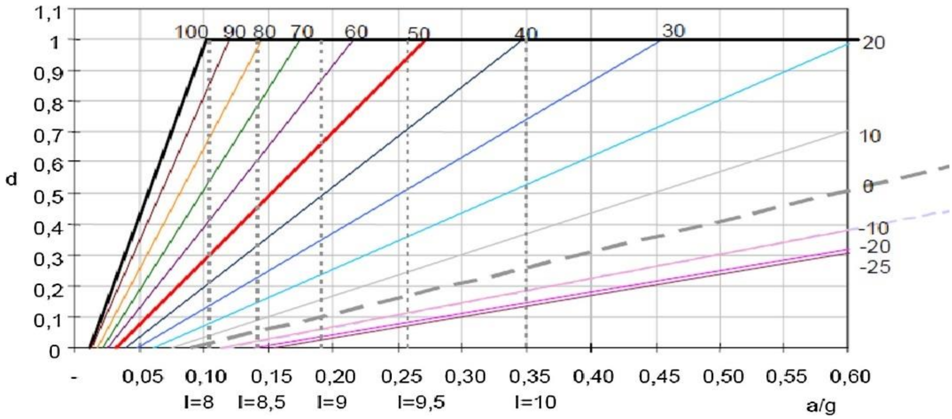


Figure 3.2.4 - Vulnerability curves proposed by Benedetti and Petrini (Benedetti and Petrini, 1984)

The European research project RISK-UE has as main objective the development of a general methodology for the seismic risk assessment of European towns. The Vulnerability Index Method was adopted as one of the vulnerability assessment procedures for seven European cities. Some modifications to the original vulnerability index procedure were applied in that a rapid screening approach was used to define the vulnerability scores of the buildings, following the guidelines of ATC-21 (ATC, 1988); indeed This approach is based on the building typology classification that is distributed into six vulnerability classes (A to F) from most vulnerable to least vulnerable typologies. Such buildings are classified into four general typologies: masonry, reinforced concrete, steel, and wooden. Besides that, it categorized the scale of damage into five grades denoted by D_1, D_2, D_3, D_4, D_5 from slightly damaged into fully collapsed. Also in this procedure, the vulnerability score was obtained from the weighted sum of eleven parameters; but some scores were directly obtained from a field assessment, while the other were based on a range of values according to historic or recent construction practices within the region, thus leading to a lower and an upper bound to I_v for each building. This method measures the vulnerability of a single or set of structural buildings by considering the typology features. The vulnerability index varies from the least vulnerable to the most vulnerable between 0 and 1. The values of the vulnerability indices are presented for each vulnerability class from A to F as a set of five values in Table 3.2.3. V_I* is the most tolerable value for each class of the vulnerability index (V_I). Where VI(--) and VI(++) are the top and bottom limits of the tolerable values, while VI(-) and VI(+)are the limits of the uncertainty range for VI*. Instead, the typological vulnerability index (VI*) had to be modified based on some structural modifiers for reinforced concrete and masonry buildings being the building's structural behaviour depends on the structural system and other factors such as construction quality, plan, and vertical irregularities, number of floors, foundations and others. These modifiers are known as the behaviour/response modification factor ΔV_m with a score symbolized as V_m. The modifying scores are attributed based on expert judgment. After some modifications, the total vulnerability index can be computed by adding or summing all the score modifiers. In Table 6 it is described the way for determining the vulnerability index value for a single building.

Table 3.2.3 - Indices of the vulnerability for the six vulnerability classes (Milutinovic and Trendafiloski, 2003)

Class	$V_i^{(--)}$	$V_i^{(-)}$	$V_i^{(*)}$	$V_i^{(+)}$	$V_i^{(++)}$
A	0.78	0.86	0.90	0.94	1.02
B	0.62	0.70	0.74	0.78	0.86
C	0.46	0.54	0.58	0.62	0.70
D	0.30	0.38	0.42	0.46	0.54
E	0.14	0.22	0.26	0.30	0.38
F	0.02	0.06	0.10	0.14	0.22

Table 3.2.4 - Procedure for EMS vulnerability index (Milutinovic and Trendafiloski, 2003)

Vulnerability Index Estimation for a Single building	
Typology V_I*	Values from Table 3.2.3
ΔV_m	$\Delta V_m = \sum V_m$
ΔV_R	DVR, Established based on expert judgment or previously observed damage data
Total Vulnerability Index	$V_I = V_I^* + \Delta V_m + \Delta V_R$

The main advantage of indirect vulnerability index methods is that they allow the vulnerability characteristics of the building stock under consideration to be determined, rather than base the vulnerability definition on the typology alone. Nevertheless, the methodology still requires expert judgement to be applied in assessing the buildings, and the coefficients and weights applied in the calculation of the index have a degree of uncertainty that is not generally accounted for. Furthermore, in order for the vulnerability assessment of buildings on a large scale to be carried out using vulnerability indices, a large number of buildings which are assumed to represent the national building stock need to be assessed and combined with the census data in a country where such data is not already available, the calculation of the vulnerability index for a large building stock would be very time consuming. However, in any risk or loss assessment model a detailed collection of input data is required for application at the national scale (Calvi *et al.*, 2006).

3.2.3 Continuous vulnerability curves

Continuous vulnerability functions based directly on the damage of buildings from past earthquakes are introduced later than DPMs; one obstacle to their derivation being the fact that macroseismic intensity is not a continuous variable. This problem was overcome by Spence et al. (Spence, Coburn and Pomonis, 1992) through the use of their Parameterless Scale of Intensity (PSI) to derive vulnerability functions based on the observed damage of buildings using the MSK damage scale, an example of continuous vulnerability function is shown in Figure 3.2.5.

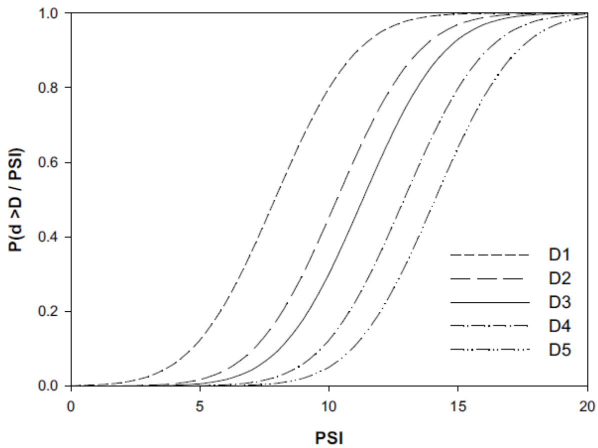


Figure 3.2.5 - Vulnerability function elaborated by Spence et al, for bare moment-resisting frames using the parameterless scale of intensity (PSI) (Calvi *et al.*, 2006)

Orsini 1999 (Orsini, 1999) also used the PSI ground-motion parameter to derive vulnerability curves for apartment units in Italy. Both studies subsequently converted the PSI to PGA using empirical correlation functions, such that the input and the response were not defined using the same parameter.

Sabetta et al. 1987 (Sabetta and Pugliese, 1987) used post-earthquake surveys of approximately 50000 buildings damaged by destructive Italian earthquakes in order to derive vulnerability curves. The database was sorted into three structural classes and six damage levels according to the MSK macroseismic scale. A mean damage index, calculated as the weighted average of the frequencies of each damage level, was derived for each municipality where damage occurred and each structural class. Empirical fragility curves with a binomial distribution were derived as a function of PGA, Arias Intensity and effective peak acceleration.

Rota et al. (Rota, Penna and Strobbia, 2006) have also used data obtained from post-earthquake damage surveys carried out in various municipalities over the past 30 years in Italy in order to derive typological fragility curves for typical building classes (e.g., seismically designed reinforced concrete buildings of 1-3 storeys). Observational damage probability matrices were first produced and then processed to obtain lognormal fragility curves relating the probability of reaching or exceeding a given damage state to the mean peak ground acceleration at the coordinate of the municipality where the damaged buildings were located. The PGA has been derived using the magnitude of the event and the distance to the site based on the attenuation relation by Sabetta and Pugliese (Sabetta and Pugliese, 1987), assuming rock site conditions.

The latter has been an important development as it has meant that the relationship between the frequency content of the ground motion and the fundamental period of vibration of the building stock is taken into consideration; in general this has been found to produce vulnerability curves which show improved correlation between the ground motion input and damage.

3.2.4 Screening methods

There are several rapid assessment methods such as the street screening method. Street screening method is the simplest rapid assessment approach. Rapid Visual Screening (RVS) as a qualitative estimation procedure can be used on a large building stock to classify the vulnerability of the structures. It is built on observations made from the building exterior, without taking into consideration the building inside. This visual survey can be done in less than 30 min (Perrone *et al.*, 2015). Based on FEMA 154 (FEMA, 2003) the street screening method is known as the Rapid Visual Screening Method. This method is the first step in the assessment before going into a detailed assessment procedure and classifying the buildings according to their construction materials and their structural systems. Basically, it is a sidewalk survey technique that worked on detecting and observing building parameters and calculating the basic structural performance score for determining the risk priorities for buildings. The process starts, with the performance score that was calculated based on the building features, such as in FEMA 154. There are 17 buildings types introduced for the RVS procedure and for each type, a Basic Structural Hazard (BSH) score was determined. The BSH score is about the probability of collapse for a building structure. After that, the BSH was modified by adding or subtracting the score modifiers (SMs) of a building. The score modifiers were based on the building properties that are affected by the seismic performance such as the number of stories, height, plan irregularity, vertical irregularity, the age of the buildings, and soil types. A building with a final score of less than 2 should undergo a more detailed investigation.

Wallace and Miller 2008 (Wallace and Miller, 2008), have applied the RVS procedure suggested by FEMA 154 for 1075 buildings in western Oregon in the U.S. Implementing the RVS procedure, they identified the potential effect of seismic hazard to public facilities. Moreover, Holmes 2010 (Holmes, 2010) investigated some of the buildings in the US that have poor seismic performance due to an inadequate seismic design by using rapid screening techniques. Meanwhile, RVS strategy was developed in numerous other nations. A few of these RVS strategies are; Canada, Japan, Turkish, Greece, New Zealand, and Indian. In Canada, the National Research Council (NRC) has proposed the widely used seismic screening procedure (Allen and Rainer, 1995). The purpose of this method was to establish the Seismic Priority Index (SPI) resulting from the addition of the structural (SI) and non-structural (NSI) indices. This screening score major factors have been; building location, soil type, duration or age of occupancy, falling hazard, and others. The SPI index is categorized into three evaluation stages, where SPI less than 10 is considered as ''low" detailing assessment, for SPI between 10 and 20, it is considered as ''medium", and for SPI higher than 20, it is considered as ''high" assessment (Cheung, Foo and Granadino, 2000; Saatcioglu, Shooshtari and Foo, 2013). In Japan, the Japanese Seismic Index approach comes in the form of three screening assessment stages to perform. In the first stage, the compressive strengths of the vertical resisting members are used to quantify the structure's response behaviour during lateral seismic loading. The second stage, the seismic capacity is evaluated by considering the dynamic properties of the resisting members only such as ductility and strength, while in the third stage, the vertical and the horizontal members (columns, walls, and beams) strength and ductility are included for evaluating the structural performance during the earthquake movements. The Index of the structure (I_s) is calculated based on the product of Basic Structural (E_0) to Irregularity Index (S_D), as well as the time or deterioration index (T). Once the Seismic Performance Index (I_S) has been determined, it ought to be compared with the Seismic Judgment Index (I_{S0}) to classify the building as adequate or not to resist earthquake forces. There are two possibilities in comparing I_S and I_{S0}, in the first one, if $I_S > I_{S0}$, this means it has low vulnerability condition and for the second one, if $I_S < I_{S0}$ it will correspond to high vulnerability condition (Otani, 2000; Albuquerque, 2008).

In Turkey, Hassan and Sozen 1997 (Hassan and Sozen, 1997) developed the Priority Index procedure for every individual building, which consisted of the column index (CI) defined as the ratio of column area to the floor area, and the wall index (WI) as the ratio of areas, between the area of shear and infill walls divided by the floor area. In addition, Yakut 2004 (Yakut, 2004) proposed a methodology based on the material and size properties, lateral resisting system, elements orientation, vertical and plan irregularities, column length, and workmanship. From these parameters, the capacity index (CI) can be computed to classify the building risk vulnerability. Bal et al. 2008 (Bal, Gulay and Tezcan, 2008) proposed the P25 Scoring Method, which tends to classify the collapse-vulnerable buildings. This method was developed based on collected data of 323 buildings that suffered different levels of damages during earthquake events. The P25 Scoring method depends on some parameters such as material quality, steel corrosion, vertical and horizontal irregularities, ground conditions, depth of foundation, seismicity, and others. Seven different scores for different failure modes, from P1 to P7, between 0 and 100 varied from worst to best, respectively.

In New Zealand, the society for earthquake engineering in 2012 recommended two stages of assessment: Initial Evaluation Procedure (IEP), and a Detailed Seismic Assessment (DSA). To perform the %NBS value it needs data to be collected such as seismic zone, soil type, construction age, and the design date of the building.

After producing the %NBS values, the assessment is completed. If the (%NBS $\leq$ 33), this implies that the building is ultimately susceptible and required a supplementary detailed and precise assessment. For %NBS of 67 or more, it means buildings are capable of resisting future earthquakes. For (33 $<$ %NBS $<$ 67) more evaluation may be required (NZSFE, 2014).

The previous RVS tools are rapid and useful for estimating building response due to earthquake loadings, but still have disadvantages and drawbacks based on the observed and watched damage information. These methodologies do not involve all the structural typologies as well as the seismic intensities, which are essential to be considered for vulnerability estimation. These methods were generally based on expert judgment and statistical data and are not very reliable.

3.3 Mechanical/Analytical methods

Although vulnerability curves and DPMs have traditionally been derived using observed damage data, recent proposals have made use of computational analyses to overcome some of the drawbacks of the methods. Indeed, the emergence of more attenuation equations in terms of spectral ordinates and the corresponding derivation of seismic hazard maps in terms of spectral ordinates, as opposed to macroseismic intensity or PGA, has not only improved the implementation of the empirical methods, but also given rise to the development of analytical methods. These methods tend to feature slightly more detailed and transparent vulnerability assessment algorithms with direct physical meaning, that not only allow detailed sensitivity studies to be undertaken, but also cater to straightforward calibration to various characteristics of building stock and hazard. The latter is a definite disadvantage of empirical methods. Such characteristics place the analytical type of loss assessment approaches in an ideal position for employment in parametric studies that aim at the definition/calibration of urban planning, retrofitting, insurance and other similar policies or initiatives.

These analytical approaches required the implementation of linear static, linear dynamic, nonlinear static, and nonlinear dynamics analyses. In this framework, to precisely assess the seismic demands of structures, the nonlinear analysis is the method that is usually required to be used. Generally, it can be categorized into two groups: Non-Linear Time History Analysis (NLTHA), and Non-Linear Static or Pushover Analysis (NLSA) (Lang *et al.*, 2018).

the NLSA has become very popular due to its simplicity. This method was initially presented in FEMA 273 (FEMA, 1997) where the Coefficient Method has been used to determine the target displacement and then it was updated in FEMA 356 (FEMA, 2009). The non-linear static analysis refers to the pushover analysis that will result in a well known curve identified as Capacity Curve. The ultimate goal of this approach is to obtain the structure's dynamic properties such as stiffness, strength, and ductility under seismic loading.

In NLSA procedure, the constructed model of the structure will consider explicitly the non-linear force and displacement behaviour of its structural elements. After that, a relationship would be developed between base shear and displacement exposing the structure to lateral forces monotonically increasing until the displacement of the model exceeded or reached the allowable displacement that described a predefined structural damage. As a definition, the allowable displacement is known as the target displacement. A global failure could happen when the slope of the curve becomes negative. From this method, the in-elastic response behaviour can be determined for an equivalent single degree of freedom (SDOF). This implies the need to transform multi-degree of freedom (MDOF) into a single degree of freedom that limits the applicability of this approach. However, this transformation would be exact only if the structure is vibrated in a single mode with constant deforming shape over time.

It was found that the procedure has some rigorous lacks in its theoretical foundation. The procedure as mentioned was based on two assumptions, firstly the structural responses were conquered by the fundamental vibration mode, secondly, the displacement vector remained constant (Zhang, Jiang and Li, 2017). These could be incorrect and not always fulfilled, and the structures nonlinear response could not be built on the first mode vibration and the constant lateral forces distributed (Triangular or Constant) over the height of the structure (Miranda, 1999). Meanwhile, it neglected the duration and cyclic influences as well as the dynamic features of the structure. Some researchers found that the procedure did not provide a precise result compared to non-linear time history analysis or either experimentally in evaluating building seismic behaviour (Kunnath and Gupta, 2000; Chopra and Chintanapakdee, 2004; Goel and Chopra, 2004; Maison and Bonowitz, 2004).

This procedure may be doubtful to be used unless it could predict the capability of the structure and estimate the safety limit states against the total failure. Nevertheless, this method has been used in a sequence of studies in assessing the structural capacity (Zacharenaki, Fragiadakis and Papadrakakis, 2013; Fragiadakis and Vamvatsikos, 2010; Shafei, Zareian and Lignos, 2011; Zameeruddin and Sangle, 2016). In recognition of these doubtful deficiencies, the non-linear static analysis was modified to achieve better seismic demand estimation, where too many things have been done to take into consideration such as the contribution of higher modes, torsional effect, redistribution of inertia forces, and irregular structures. The modification procedures have been as follows: Modal Pushover Analysis (MPA) procedure and Modified Modal Pushover Analysis (MMPA), Adaptive Modal Pushover Analysis (AMPA) procedure, Consecutive Modal Pushover (CMP) procedure and Modified Consecutive Modal Pushover (MCMP) procedure, Extended N2 procedure and the Envelope-based Pushover procedure, and Improved Modal Pushover Analysis (IMPA) procedure. Recently, Liu and Kuang (Liu and Kuang, 2017) proposed a procedure to evaluate the seismic performance and demand for tall buildings, namely Spectrum-Based Pushover Analysis (SPA).

The NLTHA is the most exact and precise method to assess the seismic performance of a structure. Recently, the computational methods were in rapid development, and the incremental dynamic analysis (IDA) as an improved and extended version of NLTHA methodology has become a powerful tool in evaluating the dynamic behaviour of the structures subjected to earthquake motions. It was proposed as early as in 1977 by Bertero (Bertero, 1977) and after that, it was studied extensively by several researchers and investigators (Bazzurro and Cornell, 1995; Bazzurro *et al.*, 1998; Vamvatsikos and Cornell, 2004; Yun *et al.*, 2002; Lin and Baker, 2013; Jalayer, De Risi and Manfredi, 2015). Also, it was approved by FEMA 2000 as a technique to investigate the global collapse capacity. Incremental dynamic analyses have lately played a significant role in studying the general behaviour of the structures, starting from the elastic response stage through yielding and non-linear response stages, until reaching the instability of the structure. Moreover, IDA gave a noticeable vision about the performance of a structure under seismic actions. Thus, a set of ground motion records based on NLTHA is usually needed to develop an incremental dynamic analysis (IDA). In which the ground motion intensity was selected for investigating the structural performance. This could be done by applying a successive incrementally increase of the seismic intensity until the structure reaches the global collapse capacity. The IDA result can be depicted by plotting the ground motion intensity (IM) vs. a structural response parameter (EDP).

The main advantages of this method are the capacity to model wide diversity of non-linear material behaviour, irregularity in structures with geometric non-linearity, pounding buildings behaviour, and higher mode effects in tall buildings that can be done precisely only with the non-linear dynamic procedure. However, this type of analysis also has disadvantages such as the need of a complex platform to create the analytical model; consumption time to accomplish the analysis, lack of supercomputers readily to do the analysis, and a large number of ground motions are necessary to perform the analysis as mentioned by (Roca, 1997; Shome, 1999; Krawinkler, Medina and Alavi, 2003; Krawinkler, Medina and Alavi, 2003).

3.3.1 Analytical DPMs and Vulnerability Curves

As already mentioned, the vulnerability curves were generally derived by using the observational damage data of previous events, but the computational analyses were much more reachable to develop this type of curve.

The fragility curves or the vulnerability curves were analytically used to evaluate the risk of the earthquake effect on the building structures. It was considered as a valuable tool to predict damage possibilities that may influence the structures. Also, it can be used as an indicator in the rehabilitation and retrofitting planning.

The earthquake and its ground motion have a huge catastrophic effect on the structural behaviour, for that reason, implementing the fragility analysis besides the non-linear analysis is the most beneficial tool to estimate the structural responses and the financial losses.

In the framework of the elaboration of analytical vulnerability curves, the NLSA and NLTHA represent the fundamental tool to elaborate vulnerability.

Singhal and Kiremidjian (Singhal and Kiremidjian, 1996) developed fragility (or vulnerability) curves and DPMs for three categories of reinforced concrete frame structures using Monte Carlo simulation. The probabilities of structural damage were determined using NLTHA with a set of ground motions. For the DPMs, Modified Mercalli Intensity (MMI) was used as the ground-motion parameter, while spectral acceleration was used for the generation of fragility functions. The major components of the methodology consist of:

- characterisation of the structure when subjected to dynamic loads;
- characterisation of the potential ground motions;
- quantification of the structural response accounting for the variability in the ground motion and the uncertainty in the structural response.

NLTHA were carried out using an ensemble of time-histories, corresponding to a given level of ground motion, for many buildings with random structural characteristics. The output of each NLTHA was used to calculate a global damage index related to a particular damage state, based on the model by Park and Ang (Park and Ang, 1985), because it is simple and has been calibrated using data from various structures damaged during past earthquakes. Statistical analysis of the damage indices led to the evaluation of the probabilities of different damage states and thus fragility functions and DPMs were evaluated (Figure 3.3.1 and Figure 3.3.2).

The analytical vulnerability curves for low-rise frames were subsequently updated based on the observational data obtained from a tagging survey of 84 buildings damaged by the 1994 Northridge earthquake, while using a weighting system (Bayesian updating technique) to take into account the reliability of different data sources (Singhal and Kiremidjian, 1998).

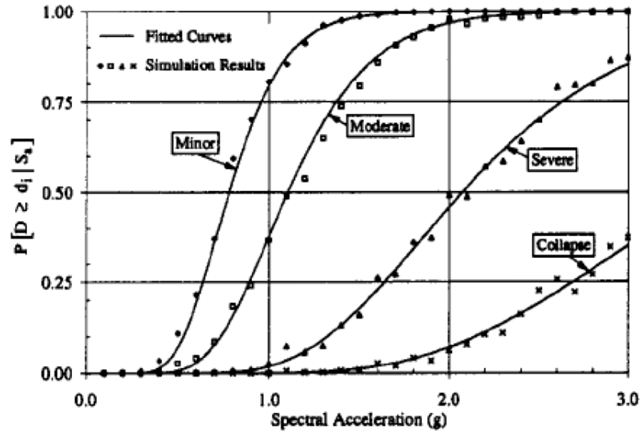


Figure 3.3.1 - Vulnerability curves for Mid-Rise frames (Singhal and Kiremidjian, 1996)

Damage state (1)	Modified Mercalli Intensity VI (2)	VII (3)	VIII (4)	IX (5)	X (6)	XI (7)	XII (8)
None	99.0	93.5	70.0	24.5	1.6	—	—
Minor	0.7	4.2	15.8	23.0	6.1	0.1	—
Moderate	0.3	2.1	12.0	36.6	33.7	4.9	0.2
Severe	—	0.2	1.9	12.5	34.6	22.3	1.8
Collapse	—	—	0.3	3.4	24.0	72.7	98.0

Figure 3.3.2 – DPMs for Mid-Rise frames (Singhal and Kiremidjian, 1996)

Masi 2003 (Masi, 2003) developed a similar procedure to characterise the seismic vulnerability of different types of reinforced concrete frames (bare, regularly infilled, and pilotis) designed for vertical loads alone. The structural models employed in this study were representative of the buildings designed and constructed in Italy over the past 30 years. A simulated design of the structures was carried out with reference to design

codes, available handbooks and known practice at the time of construction. The seismic response of the designed prototype structures, subjected to ground motions of various levels of intensity, was estimated through nonlinear dynamic analyses with artificial and natural accelerograms, while the vulnerability was characterised through the use of the EMS (Grünthal, 1998).
Rossetto and Elnashai 2005 (Rossetto and Elnashai, 2005) constructed adaptive pushover curves of European buildings and applied the capacity spectrum methodology to obtain the performance point which was then correlated to a damage state through a damage scale calibrated to experimental data. This procedure was repeated using the acceleration-displacement spectra of many ground-motion records and the variability in the structural characteristics of the buildings was modelled using a response surface method, thus leading to the derivation of analytical displacement-based vulnerability curves.
HAZUS is an earthquake loss estimation methodology including many components. It was developed by the Federal Emergency Management Agency (FEMA) under agreements with the National Institute of Building Sciences (NIBS). Estimates of building damage represent the input of another damage modules. HAZUS damage functions for ground shaking have two basic components: capacity curves and fragility curves. Capacity curves are defined by two fundamental points: the yield capacity and the ultimate capacity. The yield capacity accounts for design strength, redundancies in design and code requirements. Design strengths of model building types depend on the requirements of US seismic code provisions or on an estimate of lateral strength for buildings not designed for earthquake loads. The ultimate capacity represents the maximum strength of the building when the global structural system has reached a full mechanism. Up to yield, the building capacity curve is assumed to be linear with stiffness based on an estimate of the expected elastic period of the building. From yield to the ultimate point, the capacity curve transitions in slope from an essentially elastic state to a fully plastic state (FEMA, 2001). The capacity curve is assumed to remain plastic past the ultimate point (Figure 3.3.3).

36 different building structural typologies are considered. For each typology, values of the parameters defining the capacity curves are provided. Capacity Spectrum Method is adopted in HAZUS to evaluate the demand corresponding to a given seismic intensity. To this aim, the inelastic demand spectrum is obtained reducing the 5% damped elastic response spectrum by means of an effective damping value. Then, peak response displacement and acceleration are determined from the intersection between the demand spectrum and the building's capacity curve (Figure 3.3.4).
HAZUS provides fragility curves for damage to structural system, non-structural components sensitive to drift and non-structural components sensitive to acceleration. Fragility curves are lognormal functions defined by a median value of the demand parameter, which corresponds to the threshold of that damage state, and by the variability associated with that damage state. Four damage states are defined: Slight, Moderate, Extensive and Complete (Figure 3.3.5).

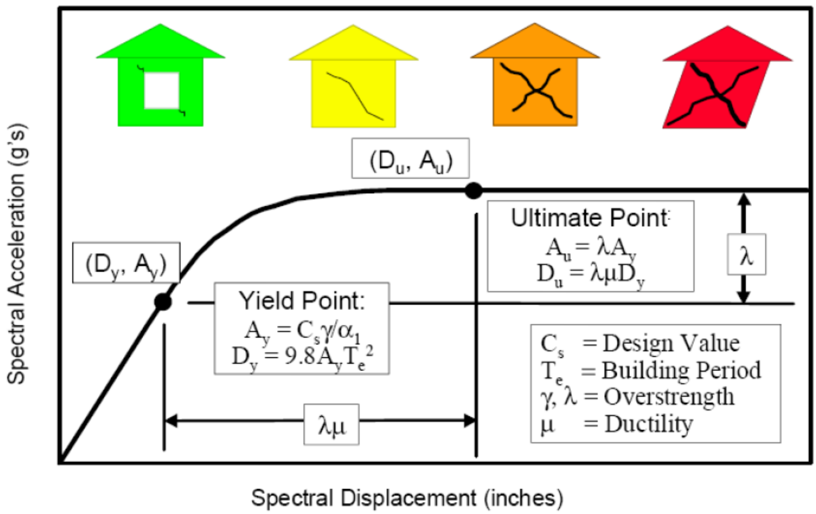


Figure 3.3.3 - Example building capacity curve and control points (FEMA, 2001)

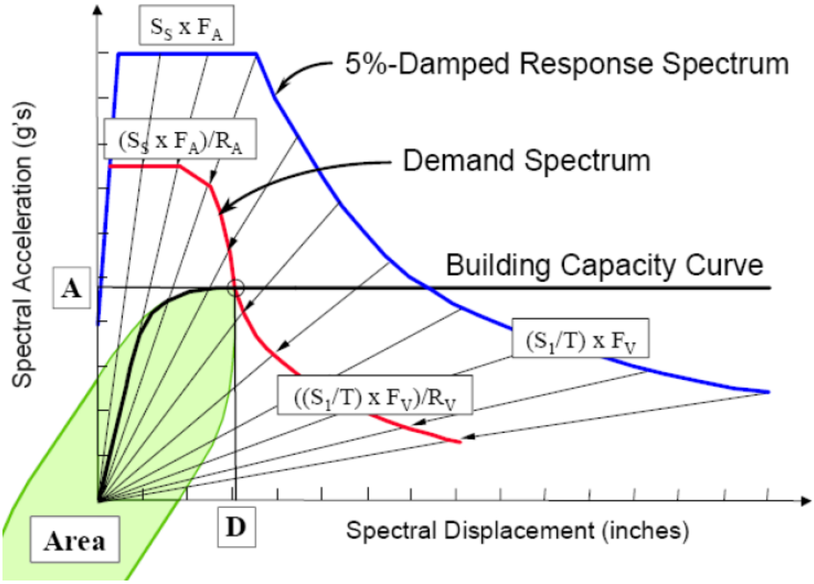


Figure 3.3.4 - Example building capacity curve and control points (FEMA, 2001)

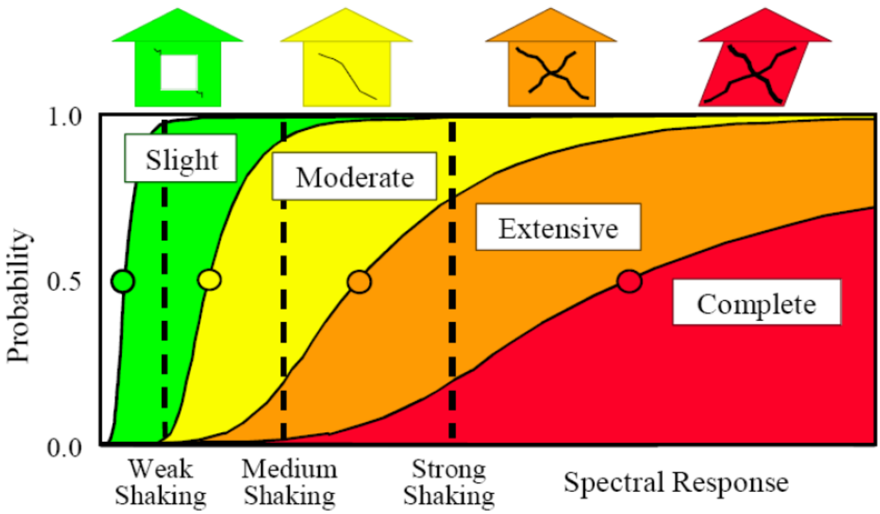


Figure 3.3.5 - Example fragility curves for Slight, Moderate, Extensive and Complete damage (FEMA, 2001)

The vulnerability curves are mostly developed for the vulnerability of residential buildings, that have been constructed as reinforced concrete (RC) and masonry structures. Vona 2014 (Vona, 2014) developed the fragility curves to examine the seismic structural response of the moment resisting concrete frame (MRCF) using two distinct analytical methods, namely, (NSA) and (NDA). With regards to this, it shows that the NDA was the greatest method to consider.

In Borzi et al 2008 (Borzi, Pinho and Crowley, 2008) it has been proposed the Simplified Pushover-Based Earthquake Loss Assessment (SPBELA) to define the nonlinear behaviour of a random population of buildings through a simplified pushover and displacement-based procedure. Displacement capacity limits are identified on the pushover curve and these limits are compared with the displacement demand from a response spectrum for each building in the random population, thus leading to the generation of vulnerability curves. At first a prototype structure representing the building class is defined, for which the collapse mechanism and, therefore, the collapse multiplier under a linear distribution of lateral forces is determined. the building displacement capacity in terms of the equivalent SDOF is evaluated for different Limit States. Then, the period of vibration for each Limit State is calculated. In order to derive vulnerability curves using this type of analytical procedure, a set of random variables is defined corresponding probability distributions. Seismic demand is defined in terms of inelastic displacement demand spectra. A Monte Carlo simulation approach is adopted, and random variables are generated. Hence, vulnerability curves can be derived for a class of buildings and for different Limit States as show in Figure 3.3.6.

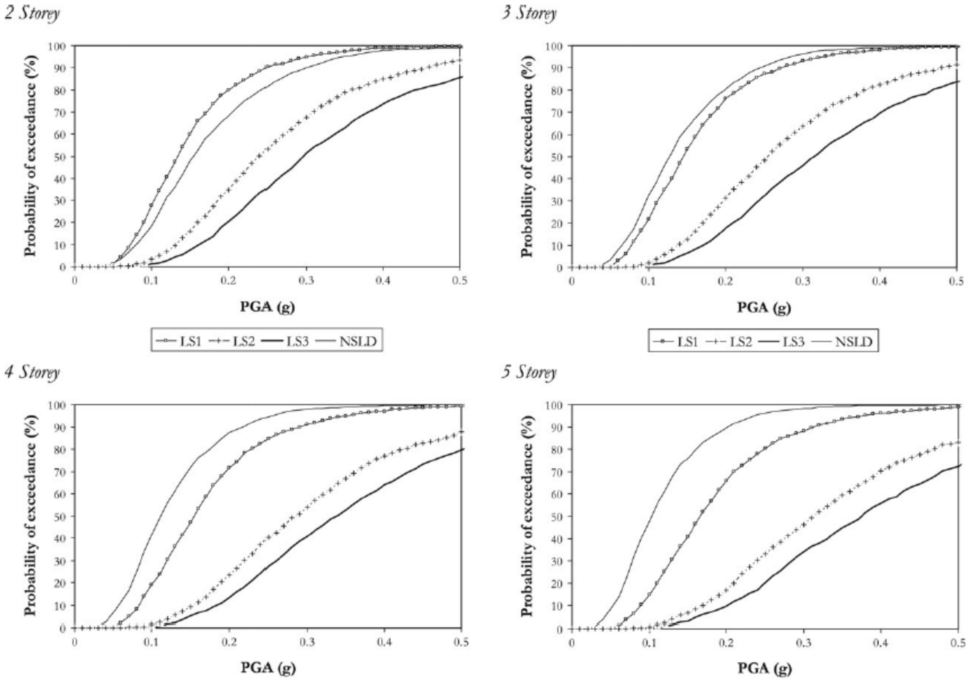


Figure 3.3.6 - Vulnerability curves derived for 2, 3, 4 and 5 storeys RC buildings (Borzi, Pinho and Crowley, 2008)

Rota et al 2010 (Rota, Penna and Magenes, 2010) propose a new analytical approach for the derivation of fragility curves for masonry buildings. The methodology is based on NLSA and NLTHA of building prototypes. Since such structure are assumed to be representative of wider typologies, the mechanical properties of the prototypes are considered as random variables, assumed to vary within appropriate ranges of values. Monte Carlo simulations are then used to generate input variables from the probability density functions of mechanical parameters. The model is defined and nonlinear static analyses are performed to define the probability distributions of each damage state whilst nonlinear dynamic analyses allow to determine the probability density function of the displacement demand corresponding to different levels of ground motion. Convolution of the complementary cumulative distribution of demand and the probability density function of each damage state allows to derive fragility curves (Figure 3.3.7).

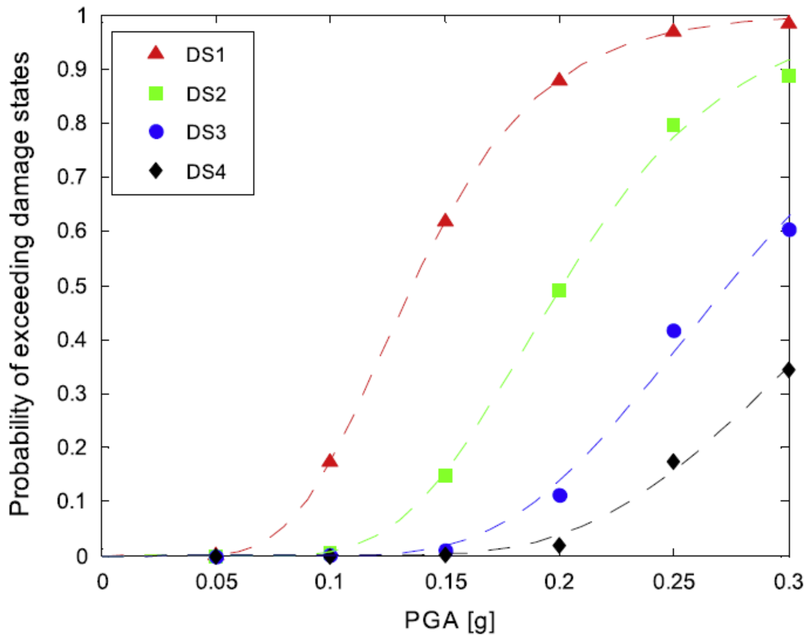


Figure 3.3.7 - fragility curves fitting the analytically derived points (Rota, Penna and Magenes, 2010)

One of the main drawbacks of the analytical vulnerability curves is that the procedure is greatly computational and time consuming; therefore, the fragility curves cannot be easily developed because of the large number of uncertainties to be considered in the modelling procedure. Nevertheless, the analytical fragility curves have been utilized to support the empirical vulnerability curves due to the lack of data related to the lack of data related to post-earthquake events, as well as the observational damages. Table 3.3.1 shows the advantages and disadvantages of empirical and analytical methods.

Table 3.3.1 - Advantages and disadvantages of the empirical and analytical methods in developing vulnerability curves (Kassem et al, 2020)

Method	Advantages	Disadvantages
Empirical	Observational damage during the event which shows realistic vulnerabilities	Missing data or lack of data, not clear vision to investigate the damages, not accurate, and mainly depend on expert decisions with different opinions
analitical	The most accurate method, all type of uncertainties can be considered	Time-consuming, very sensitive to modelling and analysis approach, and computational inefficient

3.4 Hybrid methods

Hybrid damage probability matrices and vulnerability functions combine post-earthquake damage statistics with simulated, analytical damage statistics from a mathematical model of the building typology under consideration.

Hybrid models can be particularly advantageous when there is a lack of damage data at certain intensity levels for the geographical area under consideration and they also allow calibration of the analytical model to be carried out. Furthermore, the use of observational data reduces the computational effort that would be required to produce a complete set of analytical vulnerability curves of DPMs.

Kappos et al. (Kappos *et al.*, 1995; Kappos, Stylianidis and Pitilakis, 1998) have derived damage probability matrices using a hybrid procedure, in which parts of the DPMs for each intensity level were constructed using the available data from past earthquakes following the Vulnerability Index Procedure. The remaining parts of the DPMs were constructed using the results of nonlinear dynamic analysis of models that simulated the behaviour of each building class. The time-history records were scaled to PGA values estimated by the seismic hazard analysis; intensity and PGA were correlated using empirical relationships. A global damage index was derived to correlate the structural response from the dynamic analysis (ductility factors, displacements, etc.) with loss, expressed in terms of the cost of repair. A total of 120 analyses of typical Greek buildings designed for the 1959 code were run (for 6 structures, 10 ground motions and 2 intensities), and the statistical damage results were combined with the observed damage from the 1978 earthquake in Thessaloniki.

Barbat et al. (Barbat, Moya and Canas, 1996) used the Italian Vulnerability Index Methodology for a hybrid vulnerability assessment of Spanish urban areas. A post-earthquake study was initially performed for two earthquakes with a maximum intensity of VII on the MSK scale. The structural and non-structural damage to masonry structures was analysed and correlated to the vulnerability and damage indices used in the Italian methodology. Statistical analyses were then performed to obtain the vulnerability function for the MSK intensity level VII. A computer simulation process was subsequently used to obtain the vulnerability functions at other intensity levels. Sixty hypothetical buildings with characteristics obtained from the building stock in the area were generated using Monte Carlo simulation (considering a uniform probability density function for the capacity parameters) in order to simulate the behaviour of a complete urban zone, and a simplified analytical procedure proposed by Abrams (Abrams, 1992) was chosen to model the capacity/demand relationship of masonry structures. The vulnerability index was calculated for each building, this was plotted against the global damage index (based on the capacity/demand ratios of the structural members) for the MSK intensity level VII, and a curve was obtained by regression analysis; this curve was then re-calibrated so as to match the field observations (Figure 8). The difference between the curves in Figure 8 was assumed to be due to the use of the proposed weighting factors for Italian buildings and so the weighting factors were modified such that the observed and calculated vulnerability functions matched. Once the calibration with the 60 random buildings had been carried out, the vulnerability functions for the other intensity levels were then produced using 2000 hypothetical buildings in conjunction with the calibrated weighting factors.

3.5 Masonry aggregate as a unit of analyses: Critical issues and seismic assessment approaches

Masonry is the most diffused construction material in the Italian historical centres, which are often the result of an uncontrolled urban development based on buildings erected in continuity to each other, so resulting into aggregates of constructions. These were generated by the progressive transformation of the urban tissue, in which elevation floors were added to existing constructions and plan extensions were made by adding structural units to the existing ones, so that often adjacent units shared the same boundary walls. Therefore, it is very difficult, if not impossible in some cases, to distinguish the structurally independent units and also to identify the global response of the building compound. So, seismic vulnerability assessment of masonry aggregates in the Italian historical centres represents a specific and very actual problem to be solved in order to foresee their behaviour under earthquake and, where deficiencies occur, to implement seismic protection measures.

The main difficulties of this task are related to the low knowledge level of these structures, which were in many cases built without any seismic design regulations, particularly due to the absence of drawings and/or reports. In addition, the careful analysis of these building complexes should take into account all structural units. This can be performed from the research point of view only by using either very complex numerical approaches (Senaldi, Magenes and Penna, 2010; Gambarotta and Lagomarsino, 1997) or experimental dynamic tests. On the contrary, this is an activity complicated to be developed at the design level by engineers and architects for seismic vulnerability analysis of these building groups.

Furthermore, the recent and innovative technical Italian code (NTC 2018) does not provide reliable methodologies to solve problematic issues connected to this topic.

On the other hand, in literature, starting from ''codes of practice'' for different historical city centres proposed by Giuffrè (Giuffrè, 1993), some interesting papers have analysed the current topic in order to evaluate the behaviour of masonry buildings grouped into aggregates.

In 2005 Binda and Saisi (Binda and Saisi, 2005) gave a general methodology to be followed for seismic vulnerability assessment and protection of historical masonry buildings. In particular, they prepared a report on the state of the art of research carried out in Italy in the field of cultural heritage restoration and conservation, also by focusing their attention on building compounds. After the classification of typologies of historic buildings was presented and the materials and masonry construction technologies were discussed, several mathematic models for structural analysis were provided. Finally, appropriate repair and improvement techniques for different type masonry buildings were given.

In 2004 Ramos and Lourenço (Ramos and Lourenço, 2004) addressed the seismic analysis and vulnerability of historical city centres by treating the case study of the 18th century downtown part of Lisbon. Different finite element method analyses considering the non-linear behaviour of materials were performed on a selected building compound aiming at evaluating its stability with respect to over-turning mechanisms.

Analysis results showed that the ‘‘aggregate effect’’ is felt in two ways: globally, since the force distribution obtained from analysis of each building is different from the one calculated on the whole compound, and locally, considering pounding damages due to change of building stiffness resulting from the insertion of new reinforced concrete and steel members in the structure. It was found that individual buildings are more flexible than the compound and have lower safety factors. So, ‘‘compound effect’’ is beneficial for buildings which can be studied as isolated in order to reduce the computational efforts. However, the mentioned approaches can be usefully applied when local analysis on single masonry building compounds are of concern only.
Instead, about large scale analysis of building aggregates, the work of Pagnini et al. (Pagnini *et al.*, 2011) is noteworthy. The paper discusses in particular a mechanical model for vulnerability assessment of masonry building compounds in the historical city centre of Coimbra considering uncertainties related to different factors, such as building parameters, seismic demand and model error. Capacity curves were assessed according to a probabilistic approach taking into account the variability of both structural response and seismic demand. In addition, by representing seismic demand as response spectra, vulnerability analysis was carried out with reference to several random limit states. Finally, fragility curves were derived taking into account the influence of uncertainties of different parameters examined.
Nevertheless, the need to have simpler approaches for large scale seismic vulnerability assessment of masonry building aggregates is particularly felt aiming at providing effective management tools to be used by Municipalities, especially in the prevention phase from earthquakes, for directing retrofitting interventions. In addition, the individuation of most vulnerable aggregates allows also to address aids in a rational way during the post-earthquake emergency phase.
Recent technical codes do not provide methodologies for tackling this issue and, in fact, they provide only methods to investigate the seismic behaviour of individual, independent masonry buildings. On the other hand, the scientific literature provides some studies that analyse the seismic vulnerability of masonry building compounds, considering both large scale and single scale analyses.

In (Formisano *et al.*, 2015), an easy method for large scale analysis of seismic behaviour of masonry aggregates was proposed, consisting in a new form for defining the key features to use in numerical models. After the calibration of the methodology, it was tested on an historical centre, damaged from the Aquila Earthquake. The same author (Formisano, 2017), developed a simple methodology to forecast the seismic behaviour of masonry aggregate, providing a design scheme for predicting the force distribution of each building unit.

In (Fagundes, Bento and Cattari, 2017), a study on the urban aggregates of Azores Islands was presented, wherein a numerical model was developed and investigated through nonlinear pushover analyses. The results showed the global seismic response of the compound, highlighting the effects due to the different heights of each adjacent unit.

In (Casolo *et al.*, 2017), a computational model was performed for the case study representative of Foggia and Sant'Agata di Puglia historical centres. The numerical model was investigated with nonlinear dynamic analyses, showing the differences, in terms of stress and strain distribution, obtained among each part of the compound.

With regard to regulatory framework, according to the recent relevant code prescriptions about building aggregates, (O.P.C.M. n. 3431, 2005; NTC, 2018; Circolare NTC18, 2019) standards, it is worth noting that an aggregate is composed by a group of not homogeneous structural units interacting each other during earthquakes. So, an aggregate is made by more buildings, which have a more or less efficient connection each to other. In fact, aggregated buildings can also be defined as "the combination of different units more or less connected among them that create (at least in apparent way) a unique entity difficult to be divided in parts with independent structural behaviour". For these reasons, the investigation purpose is not the entire aggregate only but also its parts, which are called "Structural Units" (S.U.), having a unitary and homogeneous behaviour toward static and dynamic loads.

Moreover, interesting and relevant standard provisions used for a lot of historical masonry buildings are the "Guidelines on Cultural Heritage" (Ministry of Cultural Heritage and Activities, 2010). Such a standard, usually employed for isolated constructions, provides indications to both evaluate and reduce the seismic risk of protected cultural heritage according to the recent seismic Italian code (NTC, 2018). In particular, in order to appraise seismic safety of mentioned buildings, three seismic analysis levels have been set-up:

- LV1 used to assess the seismic safety of protected heritage at large scale;
- LV2 used for evaluating local interventions (first mode mechanisms) on building limited parts that Italian M.D. 08 defines as “reparation or local intervention” techniques;
- LV3 used either to design interventions influencing the whole structural behaviour (defined by M.D. 08 as “upgrading or retrofitting interventions”) or to perform an accurate building seismic safety evaluation.

The department of civil protection (ReLUIS, 2010) provided a guideline for the evaluation of mechanical behaviour of the aggregate by means of the sturdy of constructive system, the interpretation of the causes of the damages, identification of the structural deficiencies which affect the seismic response in order to realize intervention able to improve the structural and seismic behaviour of the aggregate.

4 Integrated assessment of the seismic vulnerability and energy performance of existing buildings at large scale

4.1 Overview

Over the past decades, detailed individual building energy models (BEM) have widely developed becoming established modes of analysis for energy performance of the building. Only in the recent years large scale building stock models on the other side designers and energy policy makers, respectively (Reinhart and Cerezo Davila, 2016). More recently, the urgent need to reduce the energy consumption have becoming a common interest shared by major developed and developing countries and the actions to enable these global reductions are generally implemented at the city scale. This is because baseline information from individual cities plays an important role in identifying economical options for improving building energy efficiency. Numerous approaches have been proposed for modelling urban building energy use in the past decades. In this chapter it is provide a review of the categories of energy models for urban buildings and describes the basic workflow of physics-based, bottom-up models and their applications in simulating large scale building energy use (Li *et al.*, 2017).

4.2 Energy performance assessment methods of the existing buildings at large scale

The task of creating a reliable building energy model of a new or existing neighbourhood can be broken into the following subtasks: simulation input organization (data input), thermal model generation and execution (thermal modelling) as well as result validation (validation).

4.2.1 Data input

An UBEM requires the combination of serval data sets including climate data, building geometry, construction standard and usage schedules.

Researchers have recently been exploring methods of how to model local microclimatic phenomena within cities such as the urban heat island effect.

The geometry input data required by an UBEM consists of building envelope shapes and window opening ratios as well as terrain data. This information can either be

extracted from existing datasets or generated from scratch. Over the past decades, city-wide Geographic Information Systems (GIS) databases have not only become commonplace in many regions of the world but are also increasingly accessible to the general public, especially in the US. GIS shape files combined with LiDAR data or building heights (Bahu *et al.*, 2015) as well as open semantic formats can be used to automatically generate extruded or "2.5D" massing models of whole cities such as the one shown. Massing models with similar characteristics are routinely generated for architecture and urban planning projects as well.
In addition to the outer shell, non-geometric building properties have to be defined as well, including construction assemblies and HVAC systems. At the individual building level, this step routinely takes about a third of the modelling effort (Cerezo, Dogan and Reinhart, 2014) and constitutes one of the main sources of discrepancies between simulated and measured energy use due to uncertainty regarding infiltration rates, equipment loads and occupant behaviour. While these quantities can be measured for a small group of existing buildings, such detailed data collection efforts become impractical for larger urban areas. It is therefore necessary for an UBEM to abstract a building stock into "building archetypes", i.e. building definitions that represent a group of buildings with similar properties. The archetype approach has been extensively used in the context of national or regional bottom up building stock models to understand the aggregated impact of energy efficiency policies (Firth and Lomas, 2009) and new technologies (Dall'O', Galante and Torri, 2012). The generation of archetypes requires two steps: In segmentation, the investigated building stock is divided into groups according building shape, age, use, climate and systems (Ballarini, Corgnati and Corrado, 2014). In characterization, a complete set of thermal properties including construction assemblies, usage patterns and building systems have to be defined for the archetype buildings representing the previously defined groups. Depending on the scale of application and segmentation parameters chosen, an archetype may represent less than 50 up to 500,000 buildings. A notable effort to generate country-wide archetypes for 13 nations is the ongoing European research project TABULA (TABULA Project Team, 2012). The characterization of an archetype can be either based on a sample building, i.e. an actual

building within the group that is documented through an audit, or a virtual building, which is based on statistical building data and/or expert opinions.
While the actual division of a building stock into archetypes is obviously of paramount importance for the reliability of the resulting UBEM, the process typically remains ad hoc, relying on generic assumptions. The reason for this can probably be attributed to the fact that UBEM modelers do often not have access to measured individual building energy use. The usefulness of having access to such data during the generation of archetypes was dis-cussed by several groups. Aksoezen et al. (Aksoezen *et al.*, 2015) showed that older buildings can use less energy than one might expect due to their lower quality thermal properties because of modified, more energy-conscious occupant behaviour. Famuyibo et al. (Famuyibo, Duffy and Strachan, 2012) reduced the number of required archetypes from 81 to 13 by clustering actual individual building energy use. Kolter and Ferreira (Kolter and Ferreira, 2011) built a regression model based on tax assessor data that explained 75% of the variance in measured monthly energy use for 6500 buildings in Cambridge, MA. Once a set of archetypes is available, all non-geometric building properties required for a thermal model can be stored in an arche-type "template". This can be achieved by expanding established Building Information Modelling (BIM) formats such as gbXML, by adapting a GIS database format, or by using a custom data format (Bahu *et al.*, 2015; Robinson and Stone, 2004).

4.2.2 Thermal modelling

Once climate data, building massing models and archetype templates are available, they need to be combined into a thermal model, which then needs to be executed, and the results communicated back to the user in an intelligible format. Previously published UBEM workflows mainly differ in the type and detail of thermal models used as well as whether the effect of surrounding buildings is taken into account. A number of these workflows are described in the following, going from low to increasingly higher complexity. In the simplest case, an UBEM consists of single zone, steady state heat balance models of each building archetype. Simulation results for the archetypes are scaled up to the ensemble level by multiplying them with either the number of buildings per archetype (Firth and Lomas, 2009) or a foor area-weighted function of that number

(Dall'O', Galante and Torri, 2012). This modelling approach ignores that the urban context of a building can significantly affect its performance e.g. through shading, local wind patterns, etc. To consider shading as well as building compactness the SISTADT tool in combination with the INSEL simulation engine applies a single-zone steady state model to each building separately, considering its actual urban surrounding (Eicker *et al.*, 2014).

While steady-state methods are generally known to reliably predict heating loads, dynamic thermal simulation engines such as EnergyPlus, DOE2, TRNSYS and IDA-ICE are preferable for locations with notable cooling needs. Mata and Caputo accordingly used context-less single zone dynamic models to analyse archetypes in France, Germany, Italy, Spain and the UK (Caputo, Costa and Ferrari, 2013). For investigations of detailed urban design choices including mixed-use buildings, multi-zone dynamic thermal models may become necessary. In practice, this requires converting a massing model into a network of volumetric thermal zones. Same as for single zone models, multi-zone models can either be generated for archetype buildings only (Ascione *et al.*, 2013) or for each building individually so that solar shading can be considered as well. While building a multi-zone model for select archetypes is still feasible manually, this process has to be automated if applied to all buildings. For simple, rectangular buildings this is a relatively straightforward geometric operation. For arbitrary building forms, Dogan et al. (ASHRAE 90.1, 2016) recently developed an "autozoner" algorithm which automatically generates ASHRAE 90.1 Appendix G compliant multi-zone energy models from closed boundary representations (BREPs). Finally, in dense urban settings being able to model local wind speeds and longwave radiation exchange between buildings in addition to direct shading can become relevant to quantify the impact of urban microclimate on building energy use and/or occupant health. In this context, Toplar et al. and Gracik et al. recently demonstrated interesting examples of the use of computer fluid dynamic (CFD) models at the urban scale (Gracik *et al.*, 2015; Toparlar *et al.*, 2015).

The implementation of the workflows described above varies. In most cases the developers combined export/import capabilities of exiting tools such as GIS and BIM with custom scripts to generate a thermal model, execute the simulations and present them via spreadsheets or GIS applications (Frayssinet *et al.*, 2018; Dall'o', Galante and Torri, 2012). A few groups further automated and streamlined the simulation workflows to incorporate additional urban performance metrics and make UBEM accessible to urban designers and planners: SUNTOOL (Gracik *et al.*, 2015) and the CITYSIM (Robinson and Stone, 2004)are examples that combine a custom GUI with newly developed thermal simulation engines. While simulation input is a manual process in CITYSIM, it is based on CityGML geometrical databases in SIMSTADT. The Urban Modeling Interface (UMI) works as a plug-in for the CAD modeling software Rhinoceros 3D, which allows developing parametric 3D urban models and exporting and executing them in EnergyPlus while also offering daylighting, lifecycle and mobility analysis out of the same model (Reinhart and Cerezo Davila, 2016). Using a similar plug-in approach, an integrated UBEM tool for ArcGIS was developed at the ETH Zurich, capable of producing results with a custom simulation engine at multiple spatial and temporal scales (Fonseca and Schlueter, 2015).

While simple steady state simulation models for several thou-sand buildings can be executed in a matter of an hour on a standard laptop, the simulation time for thousands of dynamic multi-zone models may take days. Fortunately, the process can be fully parallelized and thus sped up using cloud computing. Less resource intensive approaches were recently proposed such as envelope simplifications and model order reduction in Modelica (Kim *et al.*, 2014), aggregating internal zones into thermal mass elements, clustering programmatic spaces in a neighbourhood into shoebox models (Dogan and Reinhart, 2013) and others. As a final step, UBEM results have to be reported back to the user in spatial and/or temporal form or otherwise. As interest in UBEM models is likely going to expand over time to include non-experts and the general public, presenting model results via web visualization techniques was explored by Giovannini et al. (Uva *et al.*, 2017). The challenge of communicating massive amounts of energy data to stakeholders as actionable information falls under the exponentially growing field of big data visualization and analysis.

4.3 Integrated assessment procedure of the existing buildings

The relationship between seismic performance and energy performance assessment, is becoming a central topic in the current scientific research, but still very few studies are available in the literature and the approaches used are very different (Park, Hwang and Oh, 2018).

Calvi et al. (Calvi, Sousa and Ruggeri, 2016) have proposed an integrated approach to evaluate energy efficiency and earthquake resilience, in which environmental and seismic factors are quantified by means of common financial decision-making variables, providing an index, "GRI" (Green and Resilient Indicator) as a function of mutual earthquake resilience and energy efficiency performance parameters.

The approach by (Belleri and Marini, 2016) quantifies the effect of seismic events on the environment in terms of carbon footprint. A same building is located in different seismic areas, considering two different conditions: energy refurbishment only; both energy and seismic retrofit.

Mosalam et al (Mosalam *et al.*, 2018) propose an application of the Performance-Based Engineering (PBE) to multi-attribute utility theory (MAUT) with the aim to select the best design alternative for a building in terms of energy efficiency, sustainability and structural safety.

An innovative life cycle cost (LCC) evaluation procedure is exposed in (Liu *et al.*, 2019), which calculates the expected cost related to the repair of damages caused by an earthquake on the building components directly connected with energy efficiency features.

In all the previously mentioned methodologies, the main problem concerns the uncertainty related to the availability and reliability of information on buildings together with the many additional variables that influence seismic vulnerability, energy performance and their interaction (Uva, Iannone and Leggieri, 2019). Moreover, the accuracy and reliability of the results of assessment methods is strongly influenced by the quantity and quality of available data (Ascione *et al.*, 2013). When defining the data collection procedure, it is also necessary to take into account that the availability and quality of information is often linked to the context of analysis (Cajot *et al.*, 2017)

PART II. DEVELOPMENT OF A BUILDING INVENTORY METHODOLOGY FOR THE IMPLEMENTATION OF THE ASSESSMENT PROCEDURES AT URBAN SCALE: INTEGRATED FORM SURVEY AND GIS-BASED APPROACH USING MULTI-SOURCE DATA

5 Construction procedure of a Georeferenced multi-source database (GMSD)

5.1 Overview

The implementation of seismic and energy performances assessments of the existing buildings at the large scale requires the collection and management of a huge amount of data. At this scale of analysis, it is not possible to use the procedures generally employed to assess single buildings, which require a detailed level of knowledge, but it is required the use of simplified procedures, easily implementable on the basis of limited information, and able to provide results with acceptable reliability and accuracy (Zuccaro & Cacace, 2015; Cacace et al., 2018).

The lack of necessary information on the basis of which performing these kinds of assessment procedures and the need to reduce the cost and time connected to the process of collection and management of huge amount of data (Vona *et al.*, 2017), remain still open questions.

In this framework, in the present chapter it is proposed a methodology of extraction, integration, and elaboration of large amount of data from different available sources able to construct a georeferenced cartographic and descriptive multi-source database in GIS environment (GMSD) on the basis of which to implement several types of assessment procedures of the current residential buildings at a large scale.

Indeed, Geographic Information Systems (GIS) allow to manipulate different typology of information derived from the overlap of several data sources, implement automatic numerical algorithms for different purposes and display general information and results about vulnerability assessment, damage and loss estimation (Vicente et al., 2011; Matassoni et al., 2013; Liu et al., 2019; Uva et al., 2019).

The proposed procedure follows a top-down approach (Swan and Ugursal, 2009), using all available datasets with different level of detail. The GMSD is constructed and used to implement a seismic vulnerability assessment of existing building stock by means of indirect procedures. Some applications are proposed for 2 cases study in Puglia: Taranto and Bisceglie.

5.2 Methodology

The proposed method allows to construct a georeferenced database of the existing building stock of an entire municipality, using information derived and integrated from different sources in order to carry out a typological classification using few meaningful typological, geometrical, structural, technological characteristics for a group of similar buildings (Zuccaro *et al.*, 2016). On this information set, it is possible automatically implement a rapid vulnerability assessment procedure in GIS environment.

The use of GIS is a powerful tool able to execute deep and integrated spatial analysis at a large scale and managing huge amount of information, enabling at the same time a rapid search, the automatic implementation of assessment procedures and finally, an effective visualisation of data and results.

The method follows a top-down approach, as shown in Figure 5.2.1, and is structured as follows:

1. Documentation retrieval, data gathering and integration from different types of sources with different levels of detail and GIS implementation;
2. Identification of homogeneous urban sectors and definition of different typological structural building classes;
3. Validation through a comparison of some typological structural building classes with the actual characteristics of sample of buildings;
4. Automatic implementation of indirect methods of seismic vulnerability assessment and elaboration of results in 3D interactive maps.

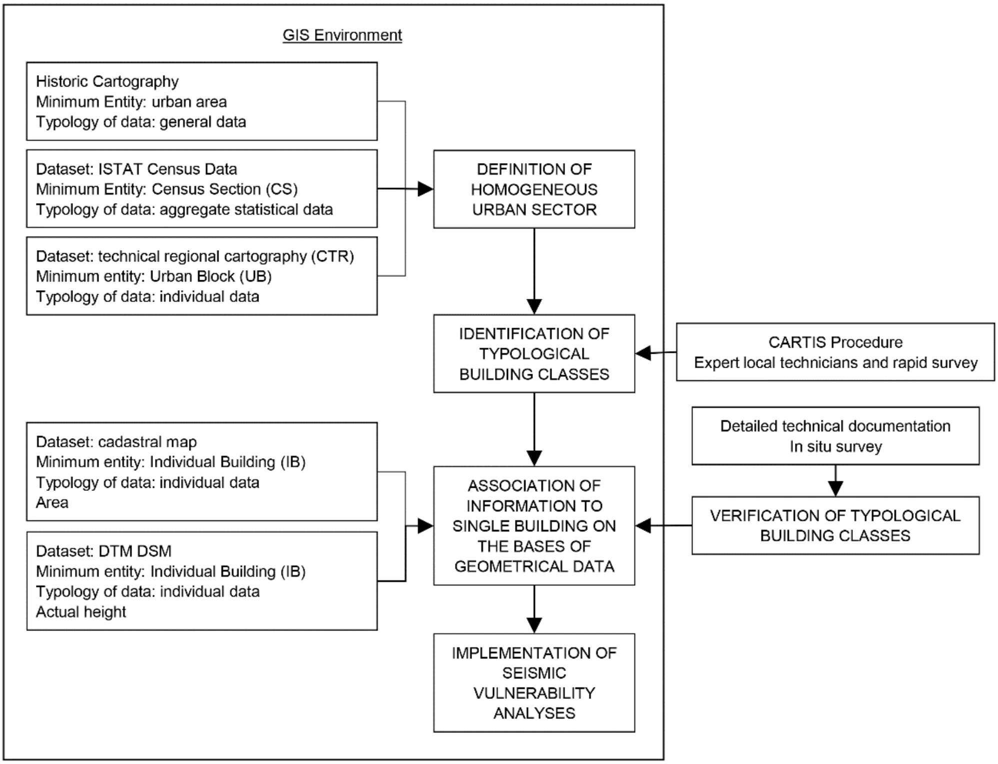


Figure 5.2.1 - steps of the procedure

5.3 Documentation retrieval and gathering data

The preliminary phase consists in the documentation retrieval and collection of all available information.

It is worth highlighting that the availability and quality of data is connected to the specific context of analysis (Cajot *et al.*, 2017), but generally it is be possible to collect information from different sources and with different level of details: statistical data, existing historical cartography, site maps, aerial photogrammetric, geospatial database, technical cartographies and rapid in situ survey. These sources are usually provided by the technical departments of municipalities, or available in web platforms in a digital format that can be easily implemented and managed directly in GIS environment.

The sources used for the application to the case study are the following:

- ISTAT dataset;
- Historic documentation and cartographies;

- Technic Regional Cartographies (CTR)
- Digital Terrain Model (DTM) and Digital Surface Model (DSM);
- Cadastral map and technical project documentation;
- ReLUIS CARTIS catalogue;

ISTAT dataset (ISTAT, 2011) is one of the main sources of statistical data about existing buildings, available for the whole Italian national territory in form of a georeferenced database that contains variables and vector files for each census section (subarea of municipal territory), defined as a polygon with associated attributes. For each census section, the number of buildings is reported together with the following features:

- Structural typology (masonry, reinforced concrete, other material);
- Class of "Age of construction" (≤1919, 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2005, ≥2005);
- Number of floors (1, 2, 3, ≥4);
- Maintenance state (bad, mediocre, good, excellent).

Historic documentation and cartographies are raster file of utmost importance for studying the time development of the urban fabric and its conformation.

The orthophotos are raster file which contain the aerial photos of territory and allows a realistic vision of the area analysed.

The Technic Regional Cartographies (CTR) are vector files in which the polygons represent the urban blocks of buildings with a set of attributes, among which:

- Typology of construction: (civil building, dilapidated building, building under construction, underground building);
- Area and height of each urban block;

The Digital Terrain Model (DTM) and Digital Surface Model (DSM) are raster files which represent the distribution of terrain's elevation data respectively without and with elements as vegetation and other artefacts and allow to derive the real height of each building, through a simple work of subtraction.

The vector files of the Cadastral maps, together with technical project documentation, if available, contain different types of information about individual buildings.

The ReLUIS CARTIS catalogue (Zuccaro *et al.*, 2016) represents an additional fundamental dataset, containing information about the typological and structural features of different building classes identified within homogeneous urban districts.
This multisource information has been managed and integrated in GIS environment, using the QGis opensource geographic information system software. Generally, among the available datasets, those in form of a vector file in which different attributes are associate to polygons representative of a part of the built space can directly implemented in GIS environment
Different Minimum Entity (ME) of information have been defined (Figure 5.3.1) for the different datasets, depending on the scale of representation of polygons, as follows:

- ISTAT dataset: Census Section (CS);
- CTR: Urban Block (UB);
- Cadastral Building Map: Individual Building (IB).

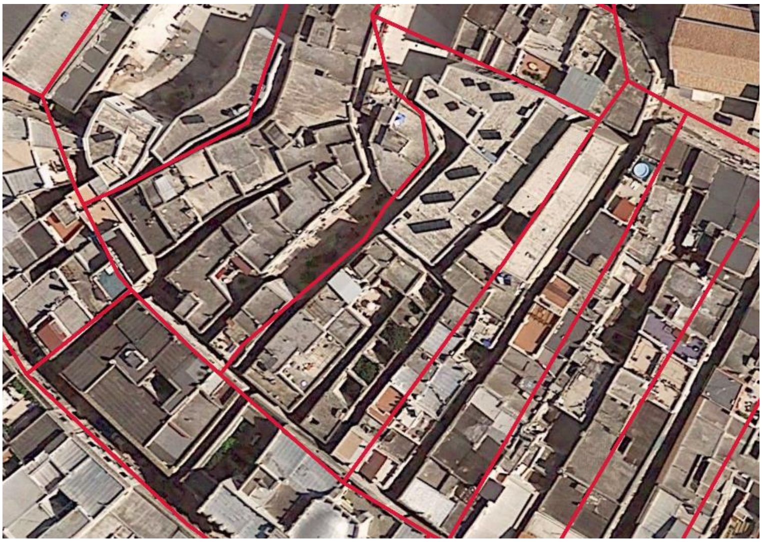


Figure 5.3.1a – Minimum entity Census Section (CS) in ISTAT database

Figure 5.3.1b - Minimum Entity Urban Block (UB) in CTR

Figure 5.3.1c - Minimum Entity Single Building (SB) in Cadastral Map

The Information related to each of these ME has a different origin, nature and level of detail. The procedure, therefore, performs first of all an integration of data among the various ME, allowing to fill in the gap of information for each level of detail. More in detail, for each CS, the information contained in ISTAT datasets about structural

typology, age of construction, numbers of floors and maintenance state, is elaborated and then associated to each UB of the CTR included in the specific CS. At the level of individual buildings, geometrical information derived from cadastral map, DTM and DSM about area and height of IB is matched with CARTIS data to recognise the corresponding typological class and then pertinent Cartis typological and structural information is associated to each IB of the cadastral map. By overlapping georeferenced vector maps with raster cartography, a check is performed and, if required, corrections or addictions of polygons and related information are applied.
The result of this operation is a Georeferenced Multi-Source Database (GMSD) in which the information is structured according to 3 different layers, each related to the pertinent scale of representation: the first contains the information at the scale of the CS, the second at the scale of UB, the third at the scale of IB. By selecting the appropriate level, different type of assessment procedure can be implemented easily and automatically for the different ME.

5.4 Integration in GIS environment and definition of homogeneous urban sectors and typology building classes

The definition of homogeneous urban sectors and typology building classes is performed according to the CARTIS procedure. CARTIS forms are filled in by an expert with the support of local technicians, and the data collected regard the recurring structural and typological features (i.e. identification of building classes) within homogeneous areas of the municipality. The information provided by CARTIS forms is integrated and verified with data of GMSD, in order to obtain a higher reliability level of information.
The general structure of CARTIS form is composed by 4 sections:
Section 0: delimitation of homogeneous urban sectors;
Section 1: identification of prevailing buildings typological classes for each urban sector;
Section 2: identification of the general characteristics of each building typological class;
Section 3: characterization of the structural elements of each building typological class, closely linked to seismic behaviour of the building type.

A homogeneous urban sector is a part of a municipality characterized by consistency in building fabric, same age of first construction and same prevalent structural and typological features.
The definition of different homogeneous parts of a municipality can be carried out on the basis of the information contained in the GMSD. The overlap of different historical cartographies allows the preliminary analyses of the historical development of the urban territory. Then, using the information associated to each CS by ISTAT datasets, it is possible to analyse the distribution of features like age of construction, number of floors, structural materials and maintenance state for the CS of the whole municipality, obtaining a reliable delimitation of the homogeneous urban sectors and the relative aggregate data. For each homogeneous urban sector, a preliminary identification of typological structural building classes is performed on the basis of this elaborated information.
Subsequently, a more detailed characterization of the typological classes is carried out by compiling the CARTIS forms with the information supplied by the local expert technicians. These data are then inserted in GMSD and associated to each IB, by matching the geometrical characteristics registered in CARTIS forms with the mean floor area given by the cadastral building map, and the height derived from DTM and DSM.

5.5 Implementation of vulnerability index method for RC and URM existing building in GMSD

For the seismic vulnerability assessment is used a simplified indirect procedure (Giovinazzi & Lagomarsino, 2001; Frassine & Giovinazzi, 2004) which required the knowledge of building typology and few others constructive parameters (e.g. age of contraction, material structural typology, number of floors, state of maintenance, position in aggregates) and thus rapidly implementable using the information available in GMSD.
The seismic vulnerability index $\bar{V}_I$ is quickly calculated according to the following equation:

$$\bar{V}_I = V_I^* + \sum \Delta V_m \qquad 5.5.1$$

Where V_I^* is the basic seismic vulnerability index and ΔV_m are modifiers coefficients. In the case of URM structure, V_I^* depend on the age of construction (Table 5.5.1) and ΔV_m depend on the state of maintenance, number of floor and taken into account the position in aggregate (

Table 5.5.2), while, in the case of RC structure, V_I^* depend on the level of design (

Table 5.5.3) and ΔV_m depend on the state of maintenance and number of floors (
Table 5.5.4). The vulnerability index V_I^* thus defined, can be easily implement for each level of information and relative ME in GMSD.

Table 5.5.1 - VI* by class of age of construction for the masonry buildings

Class	Age of construction	V_I*
I	< 1919	0,704
II	dal 1919 al 1945	0,689
III	dal 1946 al 1970	0,669
IV	> il 1971	0,667

Table 5.5.2- ΔVm are modifier coefficients for the masonry buildings

Vulnerability factor	Indicator	ΔV_m for class			
		I	**II**	**III**	**IV**
State of maintenance	good	-0,04	-0,03	-0,02	-0,02
	bad	+0,04	+0,03	+0,02	+0,02
Number of floors (height)	Low (1-2)	-0,04	-0,04	-0,04	-0,04
	Medium (3-4)	0	0	0	0
	High (>4)	+0,04	+0,04	+0,04	+0,04
Aggregate condition	isolate	-0,02	-0,02	-0,02	-0,02
	In aggregate	+0,02	+0,02	+0,02	+0,02

Table 5.5.3 - VI* by class of design level for the RC buildings

Class	Design level	V_I*
V	Absent	0,519
VI	Low	0,434
VII	Medium	0,364

Table 5.5.4 - ΔVm are modifier coefficients for the RC buildings

Vulnerability factor	Indicator	Categorie Calcestruzzo Armato		
		V	VI	VII
State of maintenance	bad	+0,04	+0,04	+0,02
Number of floors (height)	Low (1-2)	-0,02	-0,02	-0,02
	Medium (3-4)	0	0	0
	High (>5)	+0,08	+0,06	+0,04

5.6 3D interactive Tool for the queries and visualization of the information and results

The results, together with all information, are stored in the GBD as attributes associated to corresponding ME. In this way, it is possible to elaborate interactive 2D and 3D maps of the city within the GIS environment.

Based on the geo-referenced database created and after implementation of seismic vulnerability assessment, an interactive 2D and 3D maps of the city are generated within a GIS environment, which allows to visualize not only the results of seismic vulnerability assessment but also all information that can be easy searched and implemented.

5.7 Application to a municipality context of two city in Puglia: Taranto and Bisceglie

Different applications have been proposed for two municipalities in Puglia: Taranto and Bisceglie. The GMSD databased has been constructed using different available data sources manipulated in GIS environment, for the two cases study analysed. Then it has been implemented the simplified seismic vulnerability assessment at different scale depending on the available datasets. The vulnerability index has been calculated for each urban block (UB) of the municipality of Taranto and for each single building (SB) of the municipality of Bisceglie.

5.7.1 Application to the case study of Taranto

Taranto is a city located in the south of Puglia, with a population of about 200000 people. The municipality occupies a flat area of about 210 km^2 with a height above sea level of about 15 m and is characterized by medium-low seismicity. The first seismic classification dates back to 2003 and according to the OPCM 3274 (Opcm n. 3274, 2003) the area falls in seismic zone 3, characterized by medium-low seismicity.

The available datasets are the following:

- Historic cartography, provided by the technical department of municipality;
- Database in .csv format containing “Census variables” and related shapefile named “territorial bases”, available on the web platform of ISTAT (www.istat.it/it/archivio/104317);
- Technical regional cartography (CTR), vector file available on SIT-Puglia web portal (www.sit.puglia.it/);

The preliminary analysis of the time development of the urbanization of the city has been performed overlapping the available historical cartographies; 5 different zones are defined in the Figure 5.7.1.

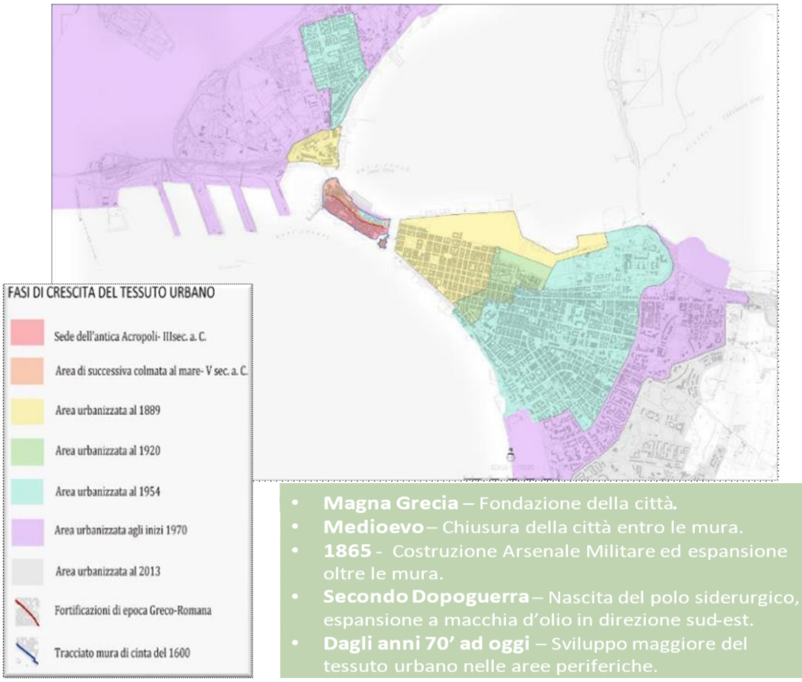


Figure 5.7.1 - Time development of the city of TARANTO

The ISTAT datasets is composed by shape file of “territorial bases” with the polygons correspondent to the census sections and the relative aggregate data stored in the “census variables”.CSV file. These 2 datasets are easily implementable and manipulable in GIS environment. On the bases of the ISTAT data, it is possible to curried out a analyses of existing buildings stock at urban scale and for each census section.

The existing residential building stock is composed by 15325 buildings, the 31% of buildings have a masonry structure (URM), while the 61% have a reinforced concrete structure (RC) (Figure 5.7.2a). About the 60% were realized between 1960 and 1990 (Figure5.7.2b), and currently show for the most part, an excellent or good state of maintenance (Figure5.7.2c).

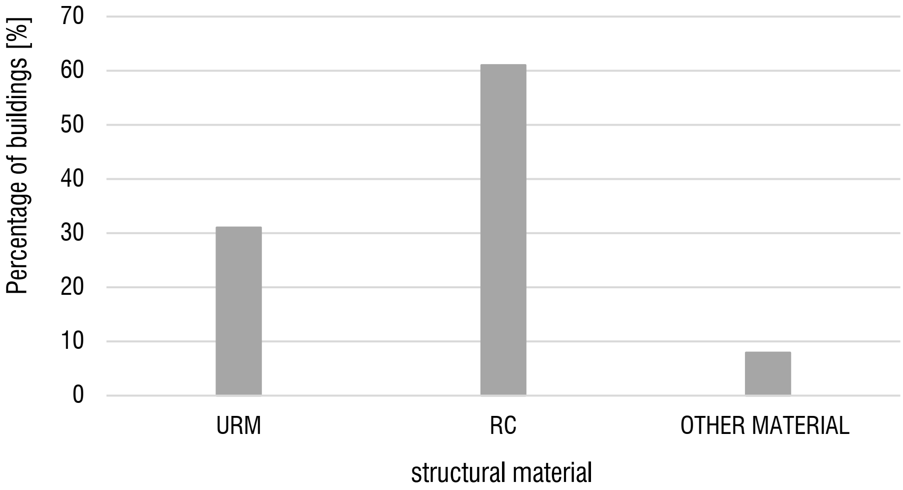


Figure 5.7.2a - percentage of buildings percentage of buildings by structural material

Figure 5.7.2b - percentage of buildings percentage of buildings by class of age of construction

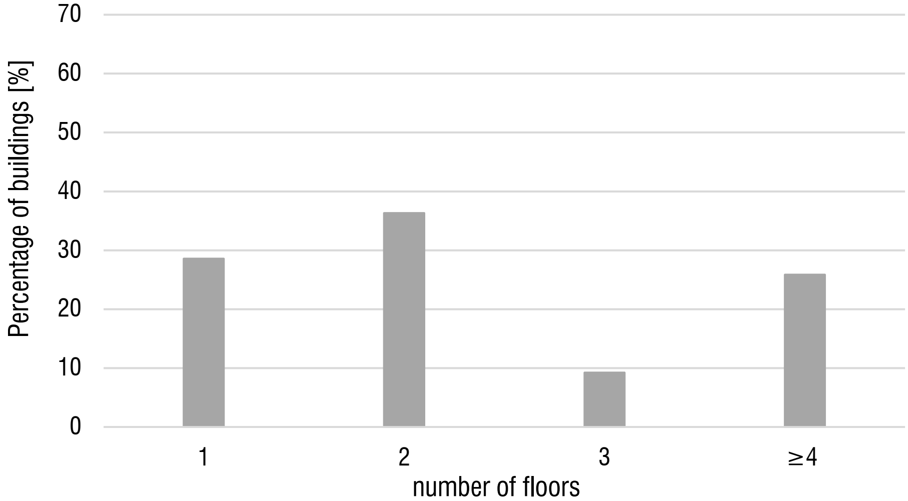


Figure 5.7.2c - percentage of buildings percentage of buildings by number of floors

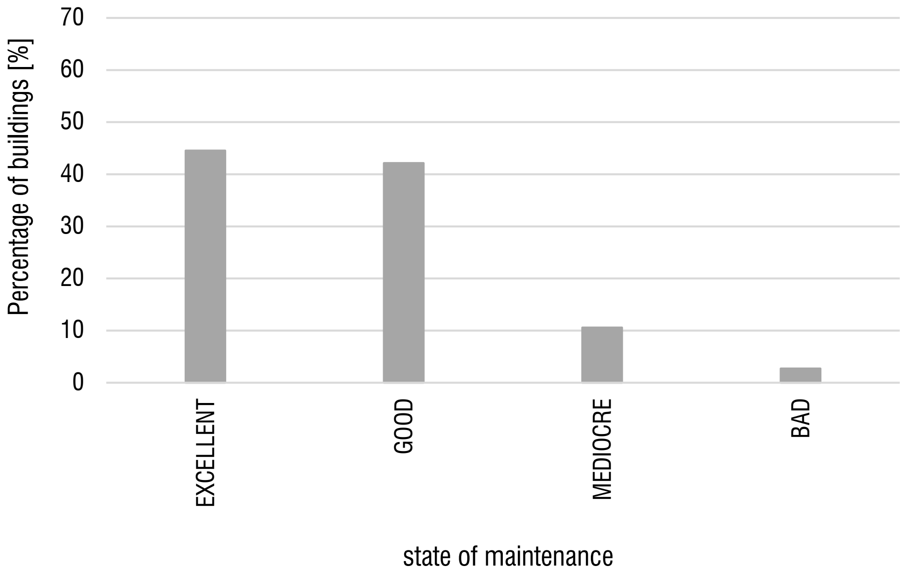


Figure 5.7.2d - percentage of buildings percentage of buildings by state of conservation

Figure 5.7.3 show an excerpt of the first phase of the construction of GMSD: the aggregate data for each census section is analysed in particular with regard to the following characteristics: structural material (E5-E6); class of age of construction (E8-E16); number of floors (E17-E20) and state of maintenance (E28-E31), being the necessary information for the implementation of the seismic vulnerability assessment according to the procedure illustrated in section 5.5. For each of the characteristic previously extrapolated, the maximum number of buildings within the urban sections have been evaluated, the characteristic of the maximum number of buildings is inherits as attributed as attribute by the polygon representative of each census section.
On the bases of this data, it is possible to obtain 2D thematic visualizations of the census sections (Figure 5.7.4) of the whole municipality and to define different sectors of the city containing census section with similar characteristics (Figure 5.7.5).
3 different homogeneous urban sectors have been defined:

- Historic centre, coincident with the oldest part of the city, contains the 1% of the entire building stock, with the almost all masonry buildings dating back to before 1919;
- Expansion zone I, is adjacent to the historic centre, and is composed by URM and RC buildings which are the 1% of entire building stock, realized between the 1919 and 1960;
- Expansion zone II, coincident with the recent neighbourhoods located in the outer zone of the city and composed almost exclusively by RC buildings realized starting from 1960. About the 85% of the entire building stock fall is this urban sector.

The implementation of CTR in GIS environment allow to analyse the urban blocks. As the first step only the polygon with attribute of the “civil buildings” have been considered, obtained 12674 urban blocks for the entire municipality. Each UB in the GMSD inherits the attributes of structural material, class of the age of construction, number of floors and state of maintenance of the census section of belonging, an additional attribute is the height calculated as the mean values of the heights of different points contain in the polygon, as shown in Figure 5.7.6. the GMSD has been populated with

data elaborated at level of the urban block which have been visualize in 2D thematic maps (Figure 5.7.7).
All the information about each census section and each urban block has been properly stored in GMSD allowing an automatically implementation of the seismic vulnerability assessment procedure described in section 5.5.
In the application to cases study of Taranto, the $\overline{V}_I$ has been calculated for 12674 UB of the CTR; the values of the indices have been discretized in 5 ranges which represent different classes of vulnerability defined as follow:

- Low (L) ($0{,}00 \leq \overline{V}_I \leq 0{,}20$);
- Medium-Low (ML) ($0{,}20 < \overline{V}_I \leq 0{,}4$);
- Medium (M) ($0{,}40 < \overline{V}_I \leq 0{,}60$);
- Medium-High (MH) ($0{,}60 \leq \overline{V}_I < 0{,}80$);
- High (H) ($0{,}80 \leq \overline{V}_I < 1{,}00$).

The Figure 5.7.8 shows the frequency distribution $\overline{V}_I$ of the urban blocks of each homogeneous urban sector. In the historic centre of the city, the 95% of the residential existing buildings are characterized by medium high seismic vulnerability, with $\overline{V}_I$ values ranging from 0,63 and 0,73. Expansion zone I and II show a similar situation with respectively the 67% and 73% of existing buildings characterized by medium seismic vulnerability with $\overline{V}_I$ values ranging from 0,57 and 0,60 and, in both cases, about the 30% of building belonging to medium high vulnerability class with $\overline{V}_I$ ranging from respectively 0,67 and 0,79, in the expansion zone I and 0,7 and 0,73 in the expansion zone II. The resalts obtained have been associated to each urban block in GMSD, this allows the rapid search and the visualization in GIS environment of the results (Figure 5.7.9).

CITY	NCS	RESIDENTIAL BUILDINGS	STRUCTURAL MATERIAL			AGE OF CONSTRUCTION									NUMBER OF FLOORS				STATE OF MEINTENANCE			
		E3	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E28	E29	E30	E31
Taranto	347	22	19	3	0	17	2	0	2	1	0	0	0	0	0	0	10	12	3	11	7	1
Taranto	348	18	16	2	0	7	9	0	1	1	0	0	0	0	0	1	11	6	2	6	10	0
Taranto	349	11	8	3	0	0	8	0	3	0	0	0	0	0	0	1	6	4	2	5	3	1
Taranto	350	19	18	1	0	1	17	0	1	0	0	0	0	0	0	1	8	10	1	1	14	3

Figure 5.7.3a - excerpt of GMSD derivation of aggregate data of the census sections

CITY	NCS	RESIDENTIAL BUILDINGS	STRUCTURAL MATERIAL	AGE OF CONSTRUCTION	NUMBER OF FLOORS	STATE OF MEINTENANCE
Taranto	347	22	E5 - URM	E8 - <1919	E20 - ≥ 4	E29 - GOOD
Taranto	348	18	E5 - URM	E9 - 1919 - 1945	E19 - 3	E30 - MEDIOCRE
Taranto	349	11	E5 - URM	E9 - 1919 - 1946	E19 - 3	E29 - GOOD
Taranto	350	19	E5 - URM	E9 - 1919 - 1947	E20 - ≥ 4	E30 - MEDIOCRE

Figure 5.7.3b - excerpt of GMSD elaboration of the attributions of each census section

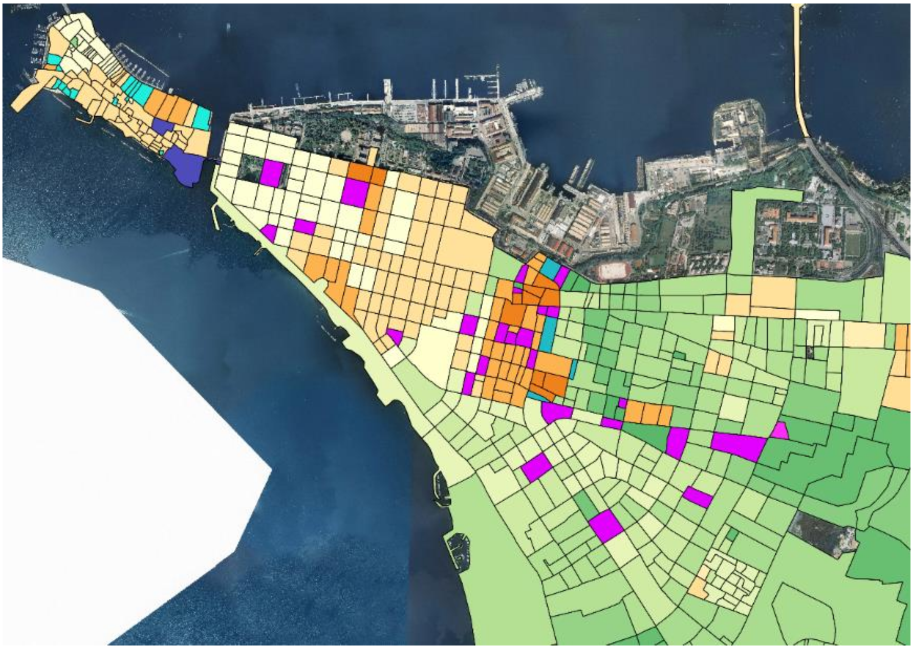


Figure 5.7.4 - thematic visualization of the census sections

Figure 5.7.5 - homogeneous urban sectors of Taranto

CITY	NCS	RESIDENTIAL BUILDINGS	STRUCTURAL MATERIAL	AGE OF CONSTRUCTION	NUMBER OF FLOORS	STATE OF MEINTENANCE	URBAN BLOCK	MEAN HEIGHT
Taranto	347	22	E5 - URM	E8 - <1919	E20 - ≥ 4	E29 - GOOD	15003	22,4
Taranto	348	18	E5 - URM	E9 - 1919 - 1945	E19 - 3	E30 - MEDIOCRE	15015	22,2
Taranto	349	11	E5 - URM	E9 - 1919 - 1946	E19 - 3	E29 - GOOD	15004	23,4
Taranto	350	19	E5 - URM	E9 - 1919 - 1947	E20 - ≥ 4	E30 - MEDIOCRE	14823	21,9

Figure 5.7.6 - excerpt of GMSD with attributions inherited by the urban blocks from census section of belonging

Figure 5.7.7 - thematic visualization of urban blocks

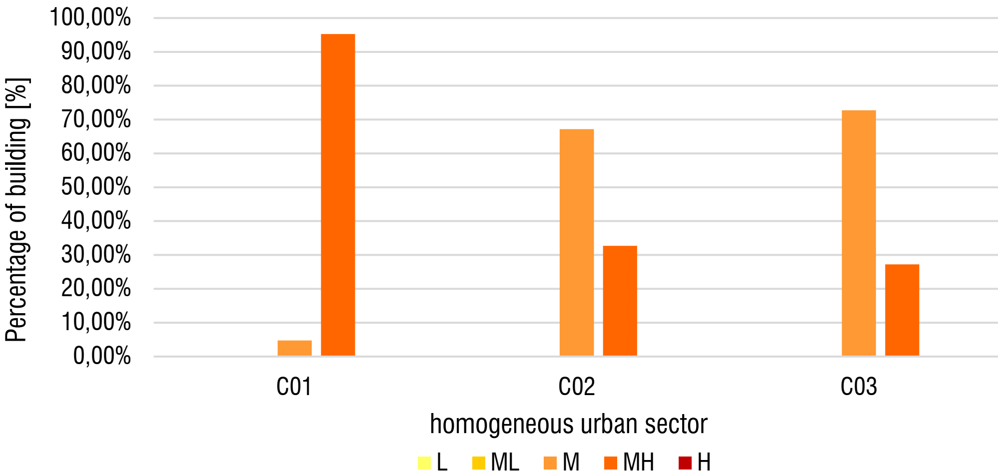


Figure 5.7.8 - distribution of vulnerability index $\bar{V}_I$ of the urban block for homogeneous urban compart

Figure 5.7.9 - 2D visualization of vulnerability indices $\overline{V}_I$ of the urban blocks

5.7.2 Application to the case study of Bisceglie

A second application has been developed for a case study of Bisceglie, in Puglia. The city has a population of about 60.000 inhabitants and a territory of about 70 km^2.

The available datasets are the following:

- Historic cartography, provided by the technical department of municipality;
- Database in .csv format containing “Census variables” and related shapefile named “territorial bases”, available on the web platform of ISTAT (www.istat.it/it/archivio/104317);
- Technical regional cartography (CTR), vector file available on SIT-Puglia web portal (www.sit.puglia.it/);
- Cadastral cartography, in two different formats: Web Map Service standard (WMS), available on Italian Tax Agency web portal and constantly update by

the authority and a vector file, supplied by the technical department of municipality (www.agenziaentrate.gov.it/),

– DTM and DSM, obtained by the Italian National Geoportal on demand, in the form of raster file with resolution of 2x2 m.

In this case, on the bases of these available sources, it has been possible to define information with regards to each of the three level of GIS entities: census section (CS), urban block (UB), and single building (SB).

According to the proposed procedure, A preliminary analysis of the historic construction development of the urban fabric has been performed by using the available historic cartographies and maps, obtaining a preliminary subdivision of urban areas.

8 different homogeneous urban sectors of the City of Bisceglie have been preliminary identified: the historic centre, located on the coastal area and clearly delimitated by boundary walls, is the medieval part of the city, and its foundation dates back to about 1000 dc., The first expansions toward the inland and the west coast started in 1920. The second expansion area and the touristic zone are located at the east of the city centre, started on 1950. The modern part of the city covers an area including inland and east coast, and the first buildings were constructed around 1970.

After these preliminary considerations based on historical information, the definition of homogeneous urban sectors has been refined using ISTAT dataset analysed directly in GIS environment: the distribution of age of construction, structural materials, number of floors and maintenance state have been analysed for the whole municipality and then for each sector.

The existing building stock occupies the 10% of entire Bisceglie territory and consists of 4922 residential buildings; about the 30% of the existing buildings has a masonry structure and 60% a reinforced concrete structure (Figure 5.7.10a); regarding the age of construction, the 13% was realized before 1919; 8% between 1919 and 1946; 7% between 1946 and 1960; 12% between 1961 and 1970; 19% between 1971 and 1980; 21% between 1981 and 1990; 11% between 1991 and 2000; 6% 2001 2005 and 3% after 2005 (Figure 5.7.10b). From these data, it is observed that 50% of the buildings was constructed before 1981, year of the first seismic classification of Bisceglie.

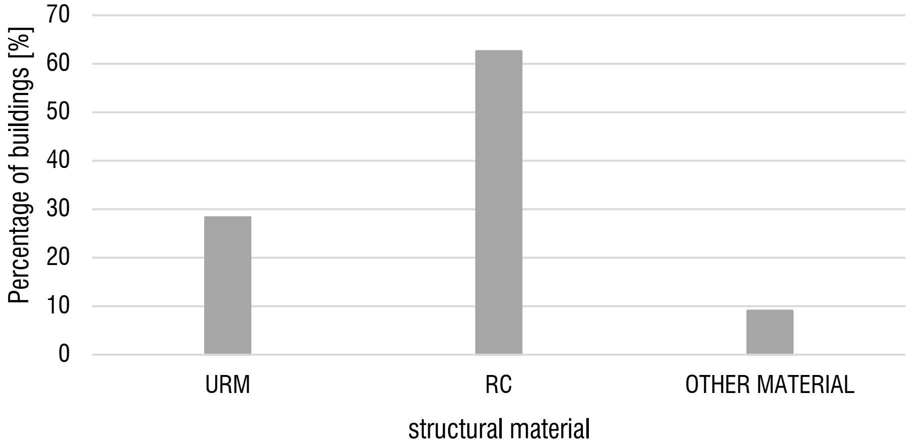


Figure 5.7.10a - percentage of buildings by structural material

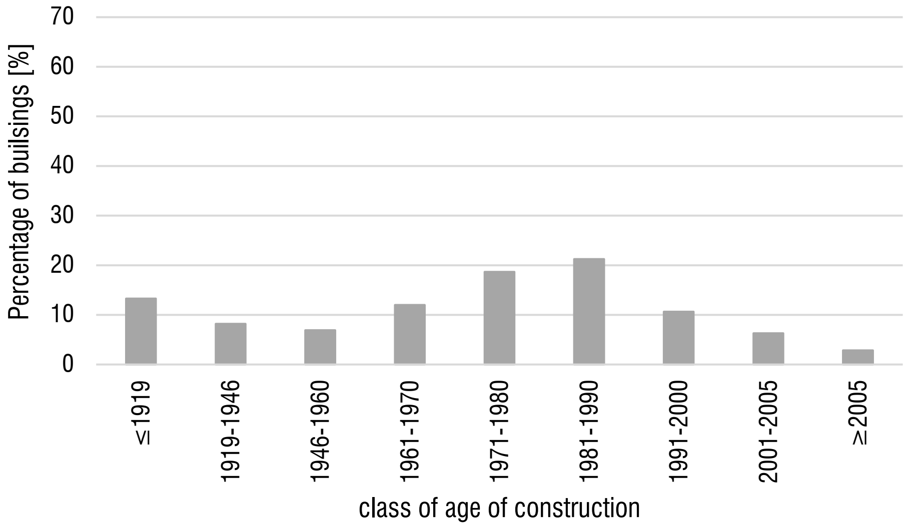


Figure 5.7.10b - percentage of buildings by class of age of construction

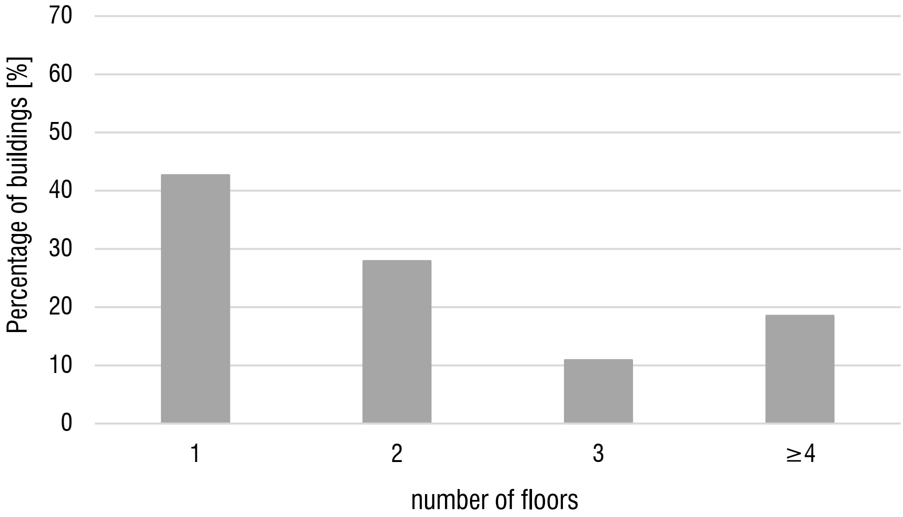


Figure 5.7.10c - percentage of buildings by number of floors

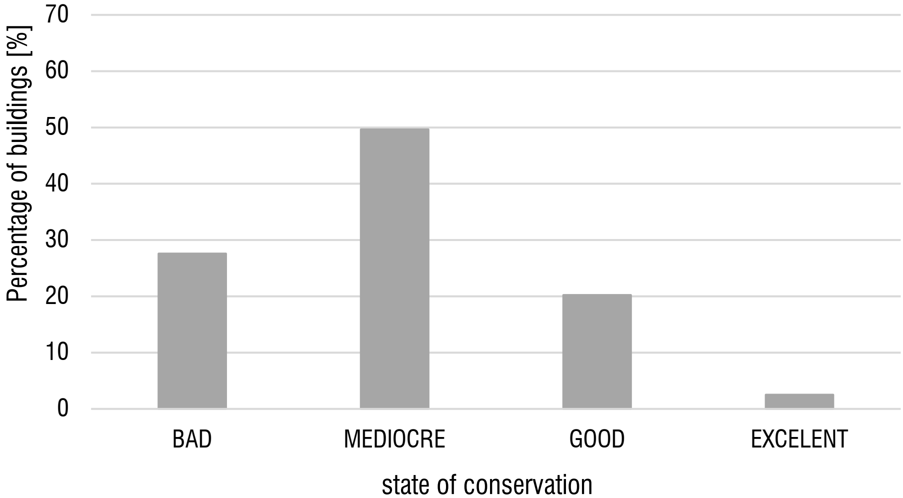


Figure 5.7.10d - percentage of buildings state of conservation

The analyses of the aggregate date given in ISTAT database for each census section have been performed according with the general framework of the procedure, as already described in the application to the case study of Taranto. Therefore, to each census section an attribute has been associated for each of the following characteristics: structural material, class of age of construction, number of floors and state of maintenance. Consequently, thematic visualization of the resalts of each census section with regard the analysed characteristics have been elaborated in GIS environment (Figure 5.7.11), to define a homogeneous urban sector on the basis of ISTAT data.
Such division of the urban territory has been verified and modified by compiling the section 0 of the CARTIS form with the help expert local technicians, obtaining the homogeneous urban sectors listed in Table 5.7.1.
Through the overlap of all this data and information the delimitation of the 8 different urban homogeneous sectors have been defined (Figure 5.7.12) and for each of them the ISTAT data have been analysed (Figure 5.7.13).

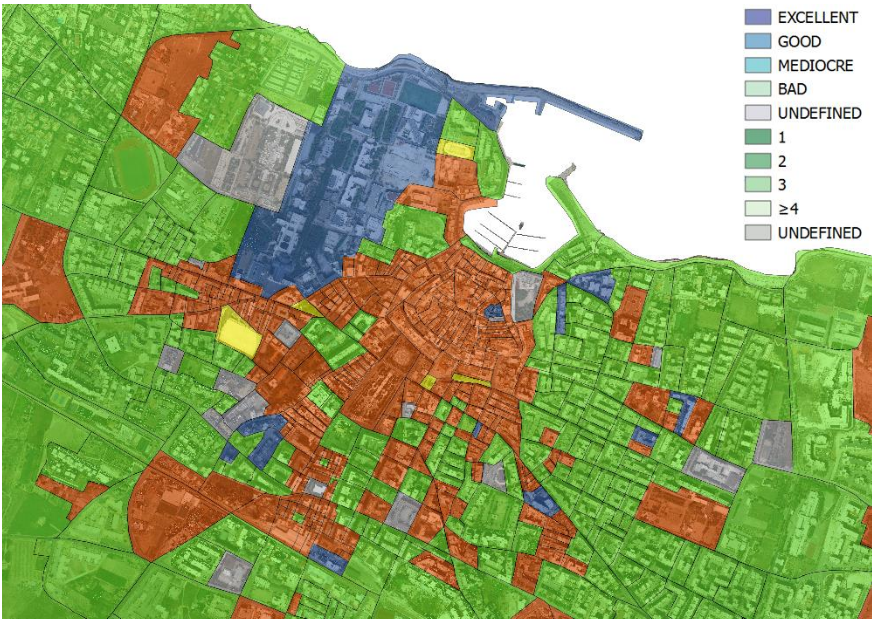


Figure 5.7.11a - Thematic visualization of ISTAT data elaborated for each census section by structural material

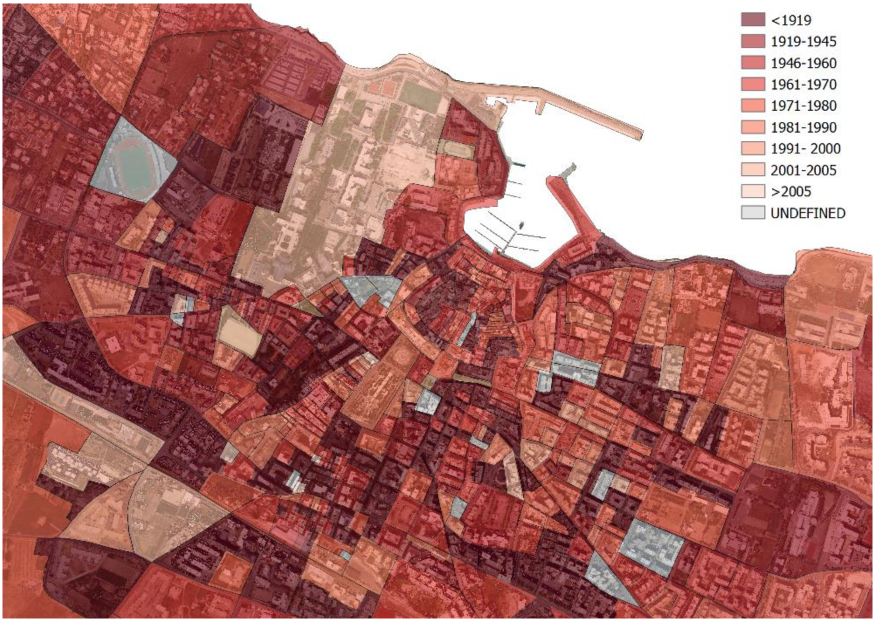


Figure 5.7.11b - Thematic visualization of ISTAT data elaborated for each census section by class of age of construction

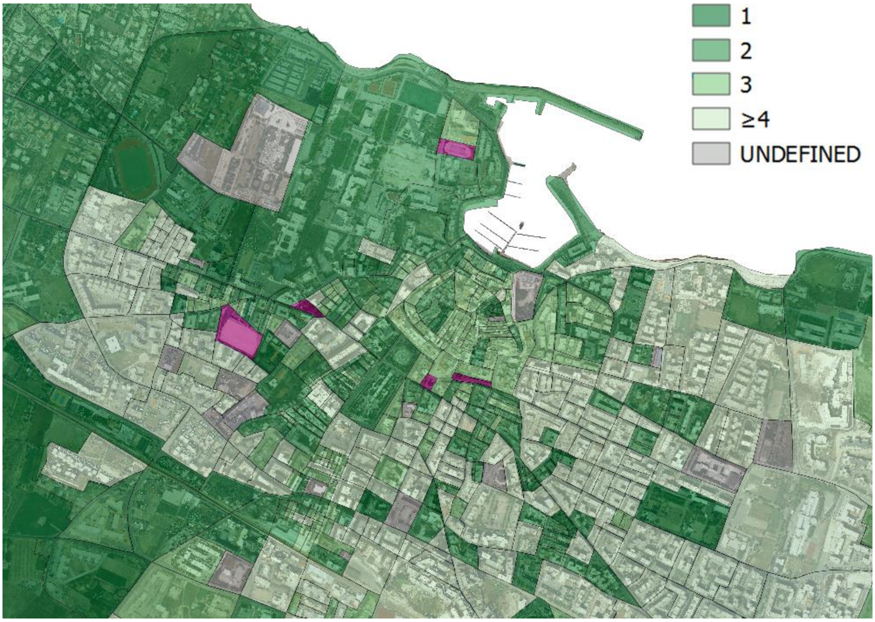


Figure 5.7.11c - Thematic visualization of ISTAT data elaborated for each census section by number of floors

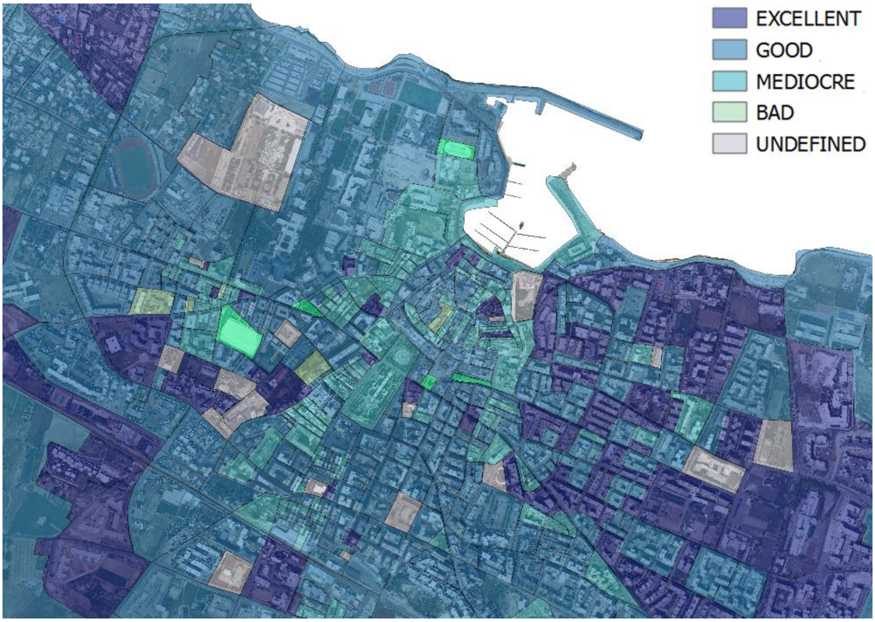


Figure 5.7.11d - Thematic visualization of ISTAT data elaborated for each census section by state of maintenance

Figure 5.7.12 - CARTIS homogeneous urban sectors of Bisceglie

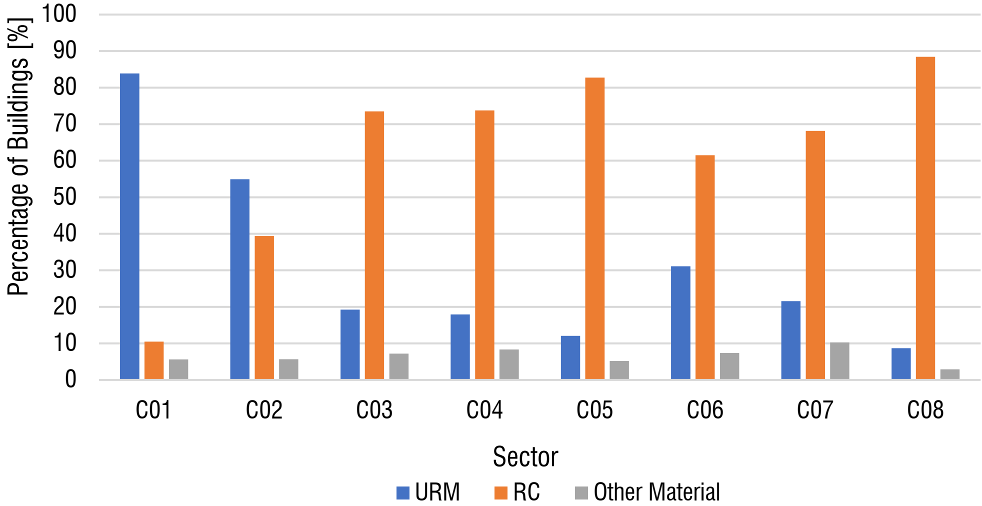


Figure 5.7.13a - percentage of building of homogeneous urban sector by structural material

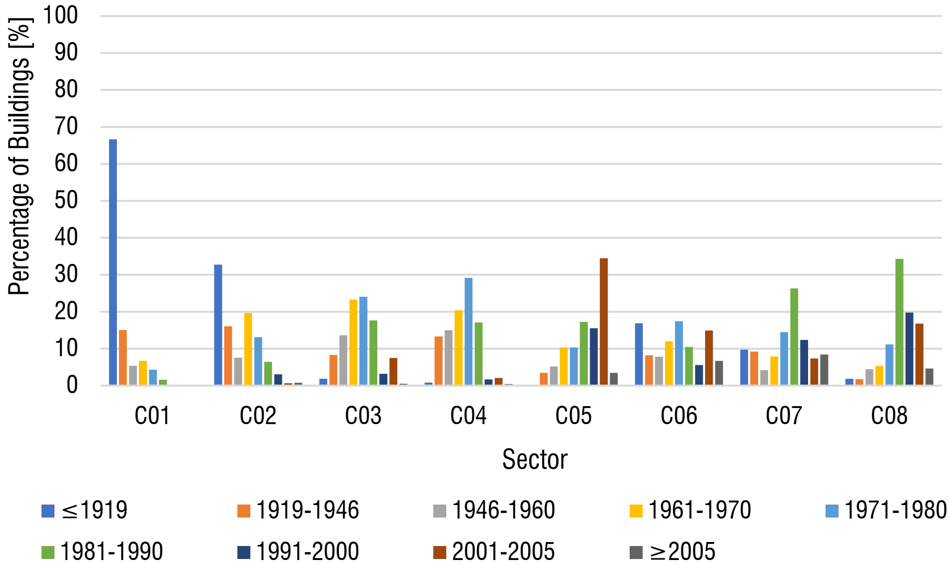


Figure 5.7.13b - percentage of building of homogeneous urban sector age of construction

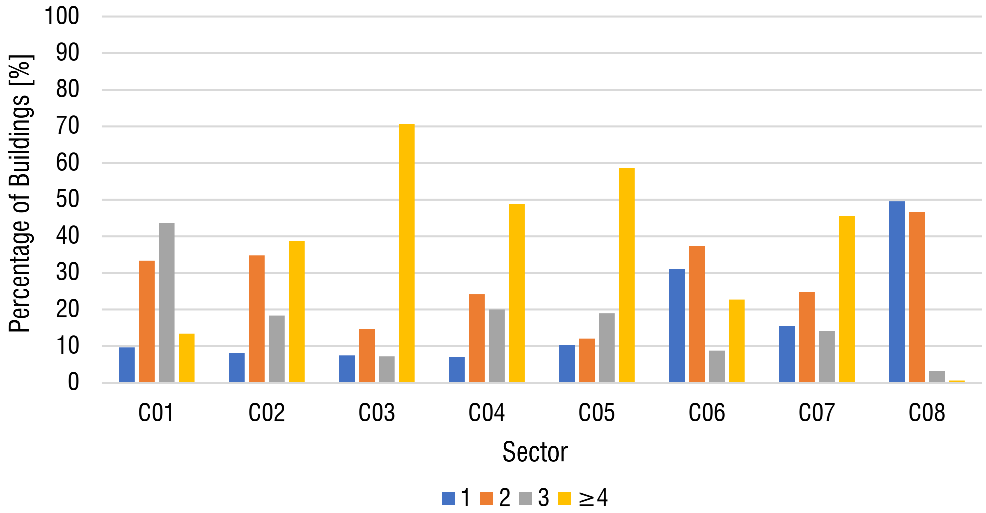


Figure 5.7.13b - percentage of building of homogeneous urban sector by number of floors

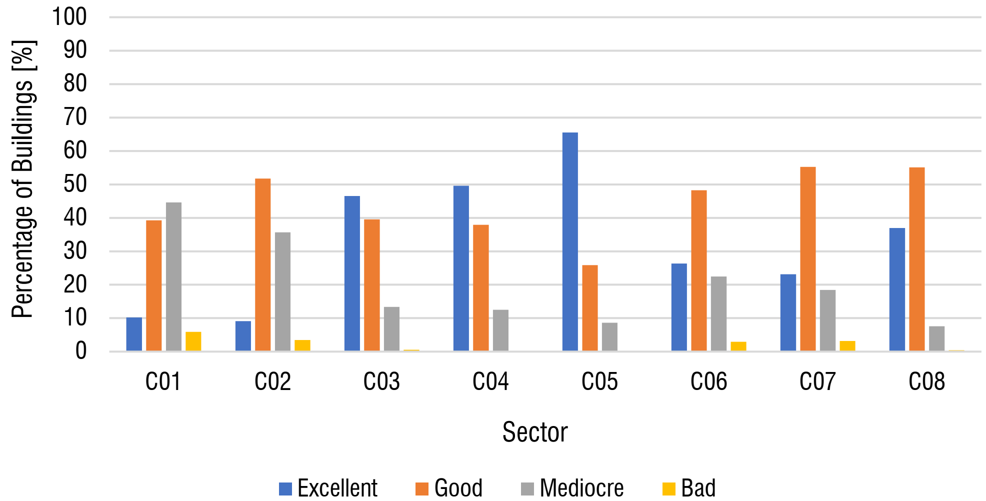


Figure 5.7.13b - percentage of building of homogeneous urban sector state of conservation

The same procedure described for the case study of Taranto has been implemented for the case of Bisceglie; using the collected data, also in this case it is possible to implement rapidly the calculation of the $\overline{V}_I$ for both levels of the census sections and the urban blocks.
The compilation of CARTIS form, allows to identify different structural typological building classes within each homogeneous urban sector representative of the entire building stock (Table 5.7.1) with relative recurrent geometrical, structural, technological characteristics, possible damage and degradation state and maintenance condition.
The integration of the data derived by georeferenced cadastral map, DTM end DSM and CARTIS catalogue allows to define the characteristics at level of individual building.
Indeed, individual buildings are identified in the cadastral map by means of polygons with relative attribute of "area", a second attribute "height" is associated to each polygon obtained by subtraction between DSM and DTM.
The individual buildings have been classified within CARTIS classes by matching the data "area" and "height" of polygon of the cadastral map general data collected in the section 2 of the CARTIS catalogue. In this way, it has been possible to associate the typological and structural features derived from CARTIS catalogue refining the data associated to each building. The information derived trough this operation has been stored in GMSD and associated to the polygons relative to the individual buildings each individual building. The $\overline{V}_I$ has been rapidly calculated for 3726 IB of the cadastral map and four class of vulnerability have been defined:

- Low (L) ($0{,}00 \leq \overline{V}_I \leq 0{,}20$);
- Medium-Low (ML) ($0{,}20 < \overline{V}_I \leq 0{,}40$);
- Medium (M) ($0{,}40 < \overline{V}_I \leq 0{,}60$);
- Medium-High (MH) ($0{,}60 \leq \overline{V}_I < 0{,}80$);
- High (H) ($0{,}80 \leq \overline{V}_I < 1{,}00$).

The Figure 5.7.14Figure 5.7.14 shows the results of the seismic vulnerability assessment plotted in a 2D map. The typological classes have similar characteristics and the value of $\overline{V}_I$ varies between 0,29 and 0,56. Specifically, 88,7% of all buildings are characterized by Medium-Low seismic vulnerability level, and 11,3% by Medium seismic vulnerability. In particular, the analysis of results with regard to different homogeneous urban sectors (Figure 5.7.15) shows that all the buildings within sectors 5 and 8 (which have the highest percentages of RC buildings) have a Medium-Low seismic vulnerability. Instead, sectors 1 and 2, which are rather homogeneous and have the highest percentage of masonry buildings, have a worst condition in term of seismic vulnerability index.

Table 5.7.1 - CARTIS Urban Sector and relative typological building classes

Urban Sector	First age of construction	Area (km^2)	Typological class (%)							
			M1	M2	M3	M4	RC1	RC2	RC3	RC4
C01 historic centre	1000	0,12	10	90	-	-	-	-	-	-
C02 first expansion	1900	0,64	30	10	-	-	34	20	6	-
C03 second expansion	1920	0,58	30	30	-	-	20	20	-	-
C04 third expansion east	1950	0,31	30	-	-	-	40	30	-	-
C05 fourth expansion east	1980	0,28	-	-	-	-	35	65	-	-
C06 third expansion west	1900	0,95	35	30	-	-	15	20	-	-
C07 fourth expansion south	1975	1,58	10		-	-	30	30	30	-
C08 touristic expansion	1950	2,14	15	-	-	-	60	25	-	-

Figure 5.7.14 - 2D visualization of building by class of vulnerability

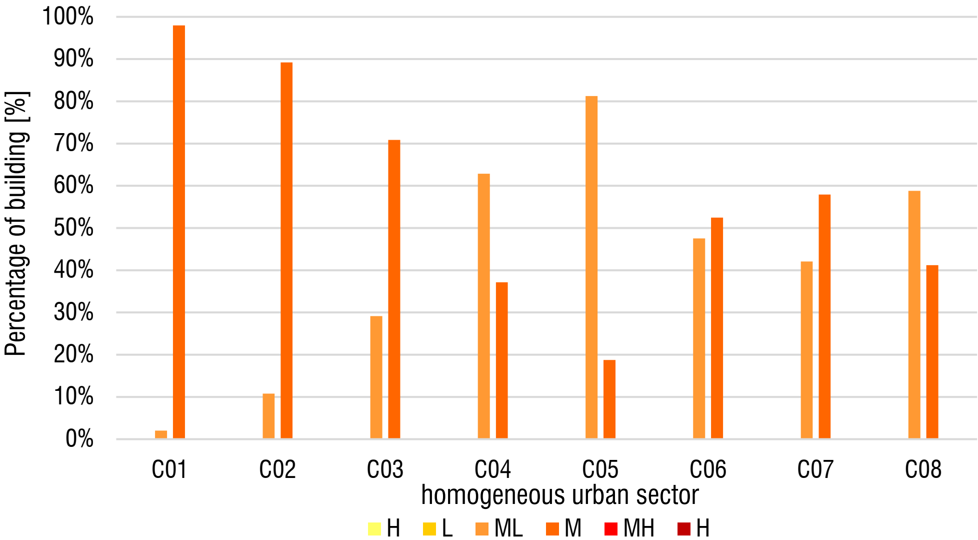


Figure 5.7.15 - Percentage of building by class of vulnerability for each homogeneous sector

For validating the database, a phase of verification of the features of some typological building classes is made by analysing a sample of buildings for which a detailed information is available.
A validation of the reliability of information thus obtained for each IB has been performed by analysing in detail a sample of buildings chosen within a same census section. The CARTIS Building form has been compiled for each building of the sample, using detailed source of information such as existing technical documentations and specific in situ survey. The results have been compared with the elaborations provided by the procedure in terms of structural and typological features, correcting, if necessary, the definition and assignment of the classification
The data have been validated using detailed information gathered on a proper sample of buildings, which have been filed and analysed one-by one.
The validation of the accuracy and reliability of the approach has been carried out by a detailed verification of the characteristics of some building classes, by filling in CARTIS forms for a sample of individual buildings composed as follows: 33 buildings of 3 different SC, in order to have the highest number possible of buildings belonging to a same buildings class.
In particular, 21 buildings are included in the census section #130 (which is entirely included in the urban sector "C02"; 5 buildings are included in the part of census section #93 belonging to the urban sector "C02"; 3 buildings are part of census section #93 in the urban sector "C06" and 4 are located in the census section #405, in the urban sector "C02" (Figure 5.7.16).

Figure 5.7.16a - census section 93

Figure 5.7.16b - census section 130

Figure 5.7.16 - census section 405

For each building of the sample, information with enough level of detail was available from the technical documentation made available by technical department of municipality or from in situ surveys specifically performed. These data have been compared with the information of the corresponding building class provided by the procedure. In particular, the comparison has been carried out on a few simple parameters: age of construction, total number of floors, underground floor and mean floor surface. In case of correspondence of characteristics, the building classification has been confirmed, whereas in case of incorrect correspondence the data of building included in GMSD has been corrected.

The comparison has shown that, on the total sample set, only the 37% of the buildings have a correspondence between their actual characteristics and corresponding class.

At the level of the single census section, in CS #130, in which a large number of buildings was analysed, the 43% have correspondence; in census section #93 only the 28% of sample and in the section 405, for which there are only 4 buildings analysed, no building have correspondence.

At level of urban sector in C02, there is correspondence only in 37% of cases and in the urban sector C06 any of 3 buildings of sample have correspondence.

The results suggest that CARTIS typological classes do not cover the whole building stock and should be modified or extended. However, increasing the number of buildings analysed, it is possible to find a matching with a typological class. For this reason, it is necessary to establish sampling rules for the verification of typological classes.

Moreover, the seismic vulnerability assessment methods at a large scale are characterized by low resolution and, generally, typological classes of the same urban sector present characteristics very similar. Therefore, further analyses will have to be made also for the seismic vulnerability results to understand the influence of an incorrect classification.

5.7.3 3D tool for the queries and visualization of the information stored in GMSD

The results obtained of the seismic vulnerability assessment have been associated in GMSD to the relative urban blocks, in the cases of Taranto, single building, in the case of Bisceglie.

In this way every minimum entity within the GMDS have the correspondent information as attributes. Using the structure of GMSD, it has been realized a 3D tool (Figure 5.7.17) which allows easily searchable and constantly implementable.
This becomes a powerful interactive tool for the knowledge, characterization and analysis at the urban scale, with an associated database that can be easily implementable, updatable and searchable.

Figure 5.7.17a - 3D tool for the queries and visualization of information and results stored of Taranto

Figure 5.7.17b - 3D tool for the queries and visualization of information and results stored of Bis-
ceglie

6 Masonry aggregates as unit of analyses: proposal and application of a typological-mechanical method

6.1 Overview

The "aggregate effect" caused by structural interaction within the building aggregates is one of the main factors that influence the seismic behaviour of the single buildings (Ramos and Lourenço, 2004).

The common approaches to this issue mainly regard the single structural units, considering the interactions due to the structural contiguity, or the entire buildings aggregates, analysing the global structural behaviour. In both cases, generally, a rigorous numerical modelling is performed using finite elements method (FEM). The result is an accurately evaluations, but implied a very detailed knowledge of the structural system and high computational effort unsustainable for applications to a large number of buildings and aggregates (Senaldi, Magenes and Penna, 2010).

The equivalent frames approach is a suitable alternative for the large scale applications, indeed, introducing strong simplifications, allows a modelling in presence of a limited information and rapid implementation of the structural analyses (Rizzano, 2011).

In this framework, using the available information stored in GIS multi-source database (GMSD) together with equivalent frames approach implement in POR2000, it is possible to perform assessment at large scale for a large set of masonry buildings and aggregates.

The mechanical methodology proposed in this chapter allows to assess the seismic behaviour of the structural typological classes of buildings and aggregates at large scale (Figure 6.1.1). The aim is to identify a simplified relation to predict the seismic behaviour of masonry buildings aggregates, starting from the limited information about the individual building.

Firstly, it has been performed a sampling of structural-typological buildings classes and analysis of the typical buildings aggregate configuration; then, it has been implemented a typological-mechanical approach for the modelling and analysis of the samples of individual buildings and corresponding aggregate configurations.

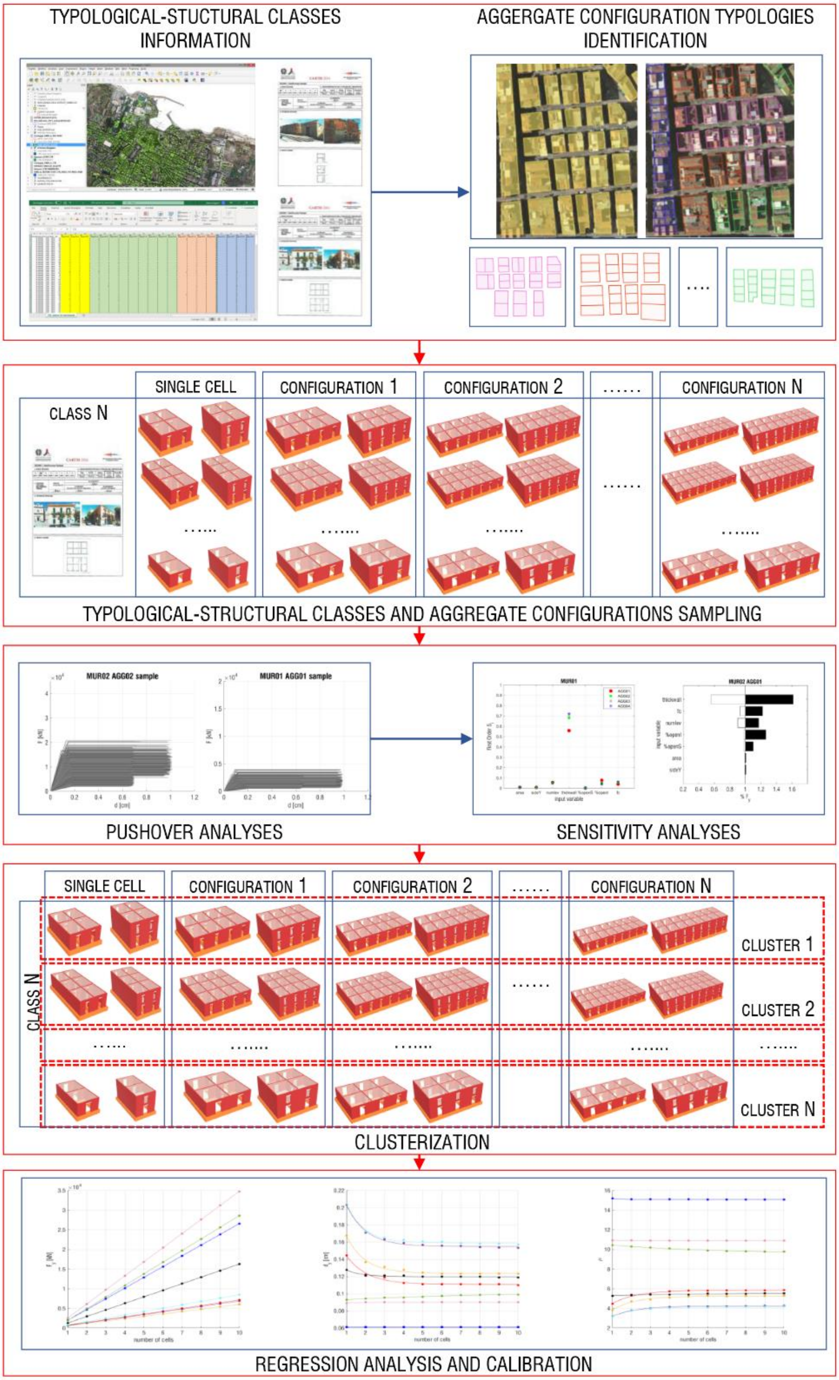


Figure 6.1.1- Conceptual steps of the proposed methodology

In particular, the information of the different structural-typological building classes has been extracted by GMSD database and used as input parameters to automatically generate the numerical models of the samples by means of a MATLAB code; pushover analyses have been implemented in POR2000 for all the models, obtaining the bilinear curves of the equivalent SDoF systems among which to define univocally the structural behaviour of each model terms of fundamental output parameters F_y, d_y and μ.
The input and output parameters have been post-processed by means of sensitivity analysis to identify clusters of buildings and relative aggregate configurations with similar seismic behaviour. The simplified relations between clusters of single buildings and clusters of corresponding aggregate configurations have been defined through regression models properly verified and calibrated.

6.2 Description of the typological-mechanical modelling and analyses

The modelling and analyses of the buildings and aggregates sample are performed by mean of a typological-mechanical approach performed using the software POR2000 (Newsoft, 2020), which implemented an evolved version of the so-called POR method (Tomazevic, 1978), based on the adoption of equivalent frames approach.
The masonry pears are considered as the only resistance elements and, hence, the critical zones in which deformations and failure mechanisms occur, without consider deformations and failure in masonry spandrels. Piers and spandrels are connected by rigid nodes and each resistant element is modelled by proper constitutive laws.
The two following fundamental assumptions are considered:

1. Shear-type hypothesis, with blocked rotations at the base and top sections of masonry pears;
2. Rigid roto-translation in-plane of slab;

The validity of both hypotheses implies a box-like behaviour of masonry structure; indeed, the first hypothesis is valid if there are transversal walls that limit the rotation of terminal sections of masonry piers; the second hypothesis is valid if masonry panels are well connected to each other implying a heavy torsional stiffness in the plane of the slab also in absence of floor.

It is worth pointing out that, these assumptions are independent from the hypothesis of infinitely stiffness of slab, indeed, even in the case of concrete floor, the stiffnesses of slabs and masonry piers are comparable. Instead, the hypothesis of infinitely stiffness of slab is fundamental for the distribution of the horizontal forces depending on the resistance capacity, stiffness and position in plan (distance from centre of rotation) of the masonry piers. In particular, the stiffness of each masonry pier, in condition of blocked rotations of bottom and top sections, is evaluated using the bending and shear deformable beams theory, as follow:

$$K_m = \frac{G \cdot l \cdot t}{1{,}2 \cdot h} + \frac{1}{1 + \frac{1}{1{,}2} \cdot \frac{G}{E} \cdot \left(\frac{h}{l}\right)^2} \qquad 6.2.1$$

Where l is the length of masonry panel, h the deformable height, E and G are respectively young and shear modulus of the masonry and J is the moment of inertia of the panel.

Other important aspect in the numerical modelling is the presence of openings which weaken the resistance of the masonry panels interrupting their continuity. This condition is taken into account reducing the effectiveness height of masonry piers on either side, considering a properly diffusion angle of stress near the windows and introducing a stiffness contribution of masonry spandrel located above and under the openings (Dolce, 1989) as showed in Figure 6.2.1.

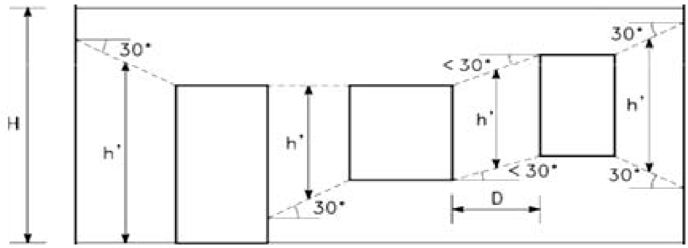


Figure 6.2.1 - definition of effectiveness height of masonry piers (Dolce, 1989)

A bilinear elasto-perfectly plastic behaviour is assumed for the masonry piers, defined in terms of strength and ductility.

As well known, until the elastic limit, force and displacement increase proportionally by means of stiffness value of the masonry panel. The elastic limit is defined by maximum elastic displacement d_e at which corresponding ultimate shear capacity V_u or combined compression and banding capacity M_u. Beyond elastic limit the capacity remains constant (equal to V_u or M_u) and the panel dissipates energy in from of plastic deformation reaching firstly damage limit state displacement d_{sld} and lastly collapse limit state displacement d_{slc} (Figure 6.2.2) in correspondence of which the panel is considered collapsed annulling its resistance.

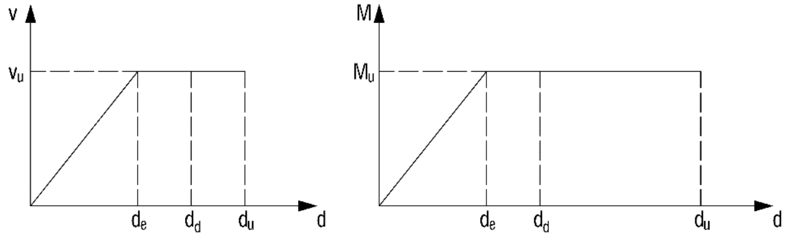


Figure 6.2.2 - Shear and combined compression and bending bilinear elasto-perfectly plastic behaviour low of masonry panel

According to Italian building code (§7.8.2.2.1, §7.8.2.2.2, NTC 2018), the combined compression and bending capacity is calculated as follow:

$$M_u = \left(l^2 \cdot t \cdot \frac{\sigma_0}{2}\right) \cdot \left(1 - \frac{\sigma_0}{0{,}85 \cdot f_d}\right) \qquad 6.2.2$$

Where l is the length of panel, t is the thickness, σ_0 is the average normal stress referred to total area of transversal section consider the presence of compressive axial force (in presence of tensile axial force $M_u=0$) and f_d is the design compressive strength equal to f_K/γ_m.

The shear capacity is calculated trough following relation:

$$V_t = l' \cdot t \cdot f_{vd} \qquad 6.2.3$$

Where l' is the length of compressed part of masonry pier, obtained on the bases of the linear diagram of compression in absence of shear strength, t is the thickness of masonry pier and f_{vd} is the design shear equal to f_{vk}/γ_m. In nonlinear static analysis, the shear strength is calculated as follow:

$$f_{vk} = f_{vk0} + 0{,}4\sigma_n \leq f_{vk,lim} \qquad 6.2.4$$

Where f_{vk0} is the characteristic shear strength of masonry (equal to $f_{vk0}/0,7$ in absence of direct determination), σ_n is the normal stress induced by the vertical loads and $f_{vk,lim}$ is the maximum value of shear strength.

The values of displacement for which the different limit states are reached, are defined as ratio of pier height h according to the Italian building code (§7.8.2.2.1, §7.8.2.2.2, NTC 2018) as follow:

- d_{slo}= 2/3 d_{sld}; corresponding to serviceability limit state (SLO) displacement;
- d_{sld}=0.003 h; corresponding to damage limit state (SLD) displacement;
- $d_{V,slc}$=0.005 h corresponding to shear collapse limit state (SLC) displacement;
- $d_{M,slc}$=0.010 h corresponding to combined compression and bending collapse (SLD) limit state displacement;

The first step of the numerical modelling is the definition of the number and interstorey height and the nodes of the structural system.

The second step is the definition of the typology of the structural elements and relative characteristic parameters.

Typology of foundations is defined by means of the geometrical dimensions, limit load on the soil q_{lim}, safety factor f_s, Winkler soil coefficient, wet cohesion, friction angle of soil, and weight of volume unit.

The masonry typology is characterized by the specific weight w, mean normal strength f and mean tensile strength f_v, young modulus E and shear modulus G, ductility d relative to the limit states, specified as the percentage of the height of panel, safety factor for nonlinear static analysis γ_M and confidence factor FC.

Type of the openings are defined with geometrical dimensions of the base b and height h, material and geometrical dimensions of architrave.

Typology of floor is defined through geometrical characteristics of rafters (spacing I, height h, base b), transversal distribution factor and dead weight.

The structural model is constructed level by level inserting between nodes foundations, at the first level; panels with relative opening and floor at the other levels.

Subsequently, as shown in Figure 6.2.3, nonlinear static analyses is executed for 8 different directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) and 2 horizontal forces distributions, constant and linear, obtaining for each structural model 16 different analysis.

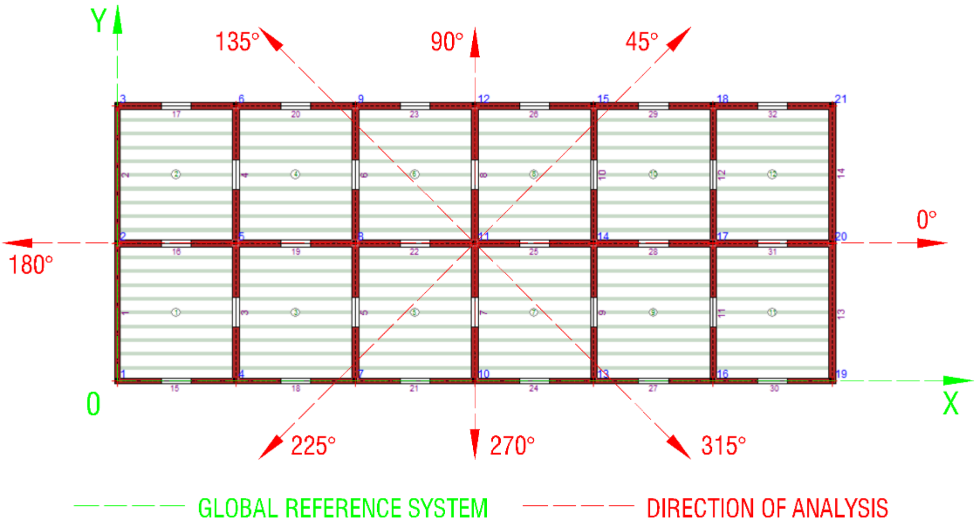


Figure 6.2.3 - Global reference system and directions of analysis

During the analysis, structure is subjected to simultaneous action of 2 different set of forces: seismic combination of structural and non-structural permanent loads, G_1 and G_2, and live loads Q_i, constant during the analysis and computed as follow:

$$\sum G_k + \sum \Psi_E Q_i \qquad 6.2.5$$

Where Ψ_E is the seismic combination coefficients of the live loads; horizontal forces distributions which increase step by step. The size of each step is properly calculated according an incremental-iterative algorithm proposed by E. Riks, which requires a low computational effort (Riks, 1979).

Generally, the panels are characterized by different geometry, stiffness and strength implying different values of capacity V_u, M_u, and ductility. For each step, the shear V_{step}, moment M_{step} and residual ductility in each pier are computed, when the collapse limit state displacement $d_{V,slc}$ or $d_{M,slc}$ is reached, the panel is considered collapsed and its contribution in global bearing resistance of the structural system is annulled. With the progression of the collapses of the panels, the structure loses progressively bearing

capacity; the analysis ends when the structure reaches a fixed minimum limit of capacity.
The achievement of the limit states during the analysis is defined trough the following conditions:

- Serviceability limit state SLO is reached when the first pier reaches a displacement d_{slo} equal to 2/3 d_{sld};
- Damage limit state SLD is reached when the first pier reaches d_{sld} is equal to ¾ of d_{slc};
- Life safety limit state SLV is reached when the first pier is reached d_{slv} equal to ¾ of d_{slc} or residual capacity of structural system is equal to 95% of maximum plane base shear or first panel reaches collapse limit state displacement d_{slc}.
- Collapse limit state SLC is reached when the residual capacity of structural system is equal to 80% of maximum plane base shear.

For each step plane base shear is calculates as cumulative of all plane shear and correspondent displacement is defined using an energetic equivalence criterium with deformation work (displacement = work/force), in order to make independent the results from the choice of a control point. The result is a capacity curve of multi-degree of freedom (MDoF) system. Using the equivalence with an elementary elasto-plastic oscillator, the MDoF capacity curve is scaled by applying modal participation factor obtaining a capacity curve relative to equivalent single-degree of freedom system (SDoF). Then, the equivalent bilinear curve is constructed; the points correspondent to F_{max} and 0,6 F_{max} are identified on the SDoF capacity curve; by joining the origin with point correspondent to 0,6 F_{max}, the elastic branch of the equivalent bilinear curve is defined with relative K_e. The yielding force of equivalent system F_y and correspondent yielding displacement d_y are obtained using equal area criterion to derive the plateau of bilinear fit, the ultimate capacity displacement d_u is correspondent to a residual capacity of structural system of 80% of maximum plane base shear. Therefore, seismic behaviour of structural system is univocally defined by means F_y, d_y, d_u and ductility $\mu = d_u/d_y$.

6.3 Definition of the statistical sample of masonry buildings and aggregates

In the proposed procedure, the numerical approach abovementioned is used to characterize the seismic behaviour of existing building typological classes, defined according CARTIS procedure (Zuccaro *et al.*, 2016), by modelling and analysing all possible case of building (hereinafter defined to as "cell") obtained as a numerical combination of geometrical, typological and mechanical characteristics extrapolated from GMSD. The same analyses are implemented to evaluate the global seismic behaviour of different building aggregate configurations obtained as assemblage of growing number of cells with the same characteristics.

It is worth to highlight that a specific CARTIS buildings structural-typological class is not coincident with actual existing buildings but is representative of a huge portfolio of possible cases of existing buildings, present in a specific urban area, with similar characteristics.

Indeed, in CARTIS catalogue, the structural-typological classes are defined by means of recurrent typological, geometrical and structural features expressed as parameters with relative range of values.

The use of CARTIS information integrated in GMSD with data derived by other sources, allows to generate a statistical sample of buildings for a specific structural-typological class. This approach is suitable to perform analyses of existing building stock at large scale in absence of detailed information about each single building.

Each building of the sample is represented with an elementary cell obtained by varying the values of certain range relative to the different parameters. Therefore, it is fundamental to select a minimum set of significant input parameters on the basis of which generate statistical sample of buildings and relative numerical model.

The strictly necessary parameters are selected among the available information stored in GMSD (Table 6.3.1 - inputs parameters for the numerical modellingTable 6.3.1).

Table 6.3.1 - inputs parameters for the numerical modelling

n	parameter	source
P_1	width (short side of block)	GIS
P_2	area	CARTIS
P_3	number of storeys	CARTIS
P_4	thickness of wall	CARTIS
P_5	Percentage of openings at upper floor	CARTIS
P_6	Percentage of openings at ground floors	CARTIS
P_7	Mean compressive strength	Tab C.8.5.I Circolare esplicativa NTC18

The range of values of the width of aggregate is defined consider the recurrent values of short side length of urban blocks of the CTR belonging to the same homogeneous urban sector.

The other geometrical parameters are derived from CARTIS catalogue where, the respective range of values are defined in term of minimum and maximum values.

The mechanical characterization of the masonry is made through the values of compressive strength extrapolated by Table C.8.5.I available in Italian Guideline of Italian building code (Circ. Esp., 2019), in which reference values of the mechanical parameters are reported for the most recurrent masonry typologies in Italian territory. It is possible to assume a plausible masonry typology coherently with the information about age of construction, location of buildings and typological futures of wall.

The range of values of each parameter PAR, defined trough minimum and maximum value, are then further discretized to taken into account other possible intermediate values (Eq. 6.3.1).

Within a specific typological class, the buildings aggregate configurations are construed by successive repetition in plan of equal cells obtaining a rowhouses typological aggregates constituted by a series of structural units.

Consequently, within the same CARTIS building class, for each different configurations (single cell and aggregate configurations), the statistical sample of buildings is composed by a number of numerical models $N_{models,sample}$ computable using Eq. 6.3.2 (Uva, Ciampoli, *et al.*, 2019), obtained by varying the values $X_{P,i}$ of each P_n input parameters.

Within a specific homogeneous urban sector, considering a number of CARTIS masonry classes n_{class} and a number of cells n_{cells} in the different aggregate configurations for each class, the total number N_{TOTAL} of numerical models is computed according to the Eq. 6.3.3.

$$P_n = [X_{P,1}, X_{P,2} \ldots\ldots, X_{P,i}] \qquad 6.3.1$$

$$N_{model,sample} = \prod_{n=1}^{n_P} i_{P_n} \qquad 6.3.2$$

$$N_{TOTAL} = n_{class} \cdot n_{cell} \cdot N_{model} \qquad 6.3.3$$

6.4 Pushover analysis and post-processing of outputs

Pushover analysis is performed for each model of the sample in POR2000, obtaining N_{TOTAL} bilinear curve for 8 directions and 2 horizontal forces distributions, constant and linear. The bilinear curve is defined in terms of F_y, d_y and μ (d_u/d_y); these 3 fundamental output parameters identified univocally the seismic response of a structural system correspondent to a specific numerical combination of the values $X_{P,i}$ of the input parameter P_n.

When the analyses are implemented for a sample of models, the ranges of values of the output parameters F_y, d_y and μ are directly proportional to the number of input parameters and relative range of values.

The analysis of the whole sample of N_{TOTAL} models and of the sample of each structural-typological classes MUR0n and different aggregate configurations, implies an excessive variability of the range of values of the F_y, d_y and μ. It must be made a further clusterization to reduce the range of variability of the output parameters, considering clusters of models with similar characteristics.

Therefore, it is necessary to identify which of the 7 input variables have more influence on the range variability of the output F_y, d_y and μ.

The sensitivity analysis allows to study the influence of uncertainty of the inputs of a model on the uncertainty of the outputs (Saltelli *et al.*, 2004).

In the framework of proposed methodology, the use of sensitivity analysis allows to identify the most influent input parameters on the output parameters F_y, d_y, μ. The aim is to shrink the number of input parameters, considering only ones that most affected response of structural system (Choudhury and Kaushik, 2018).

Three different methods suggested in literature are used:

1. The first order sensitivity index S_i and total effect sensitivity S_{Ti} index; the calculation of these indices are based on a probabilistic variance-based sensitivity analyses and quantifying the fraction of the variance of the output dependent on each input parameter treated like a probabilistic variable.

   The first order sensitivity index, also called first order Sobol' index S_i (Sobol′, 1993), indicates the main effects contribution of each input parameter to the variance of an output variable, and is defined as follow:

   $$S_i = \frac{Var[E(Y|X_i]}{Var(Y)} \quad 6.4.1$$

   Where Y is the output variable; X_i input variable, $Var[E(Y|X_i)]$ variance of the expectance of Y conditioned on X_i and Var(Y) the variance of Y. in this case, only the first-order effects is considered neglecting the influence on the output variance due to the mutual interaction of input parameters (higher-order effects).

2. The total effect sensitivity index S_{Ti} accounts first-order effect and all higher-order effects to the output variance due to interactions between input parameters, the S_{Ti} index is calculated as follow:

   $$S_{Ti} = 1 - \frac{Var[E(Y|X_{\sim i})]}{Var(Y)} \quad 6.4.2$$

   Using S_{Ti} it is possible to establish which parameter can be fixed anywhere over its range of variability without affecting the output. The parameter is a noninfluential factor when $S_i \approx 0$ and $S_{Ti} \approx 0$ (Sobol' *et al.*, 2007).

3. Tornado Diagram Analysis (TDA) is a deterministic sensitivity analysis; the input parameters are considered as deterministic variables which values are defined in a certain range. Each output of a model is evaluated by varying the value of one input parameter at a time (respectively equal to minimum and maximum value of relative range), while the other ones are fixed equal to their mean value. The result is represented in tornado chart composed by bars which

length represents the percentage variation of average value of each outputs F_y, d_y and μ.

The 3 method are implementing for each CARTIS class, aggregate configuration, direction and horizontal forces distribution, determining which of 7 input parameters have most influence on the outputs F_y, d_y and μ.

The Clusterization is performed for each CARTIS class and aggregate configuration; the clusters are composed by the models of the sample with equal values $X_{Ps,i}$ of the P_S input parameters selected as the most influent in the sensitivity analyses.

The number of clusters obtained $N_{models,cluster}$ for each CARTIS class and aggregate configuration and the relative number of models $N_{cluster,model}$ are computed as follow:

$$N_{cluster} = \prod_{i=1}^{n_{P_S}} i_{P_S} \tag{6.4.3}$$

$$N_{models,cluster} = \frac{N_{model,sample}}{N_{cluster}} \tag{6.4.4}$$

The simplified relation between the single cell configuration and relative aggregate configurations it is defined considering the correspondent clusters of the same CARTIS class. For each cluster it is calculated the mean value of the correspondent output F_y, d_y and μ, and reported in the same plot to identify the best fitting curve by means of regression analysis. The relations defined are then calibrated considering further aggregate configurations with a highest number of cells.

6.5 MATLAB Code for the automatic implementation of the procedure

The common approaches to the numerical modelling, analysis and post-processing would be extremely burdensome due to a very large number of models which could be generated by means of the abovementioned methodology.

Suitable procedure is required to automatize the process, able to generate the numerical models, analyse and elaborate the results automatically, minimising the computational burden.

A proper MATLAB code has been elaborated to automatically implement the methodology according to the following steps:

1. Generation of N_{TOTAL} structural models obtained as numerical combination of the range of values of the input parameters;
2. Implementation in succession of the models in POR2000 and pushover analysis obtaining N_{TOTAL} bilinear curves and Extrapolation of the output parameters of the entire sample;
3. Identification of the n_{Ps} most influent input parameters on variation of output parameters by mean of sensitivity analysis;
4. Clusterization of the sample based on the P_S input parameters and computation of mean values of the output parameters for each cluster;
5. Definition and calibration of the best fitting regression model of the mean value of the output parameters of the clusters of the single cell configuration and relative aggregate configurations;

STEP 1. the numerical models are defined in a .TXT file coded according a specific structure required by POR2000. N_{TOTAL} files in .TXT format are compiled by varying the values of the input parameter defined as array variables obtaining all possible numerical combinations for the entire sample.

The structure of .TXT file is divided in 3 following fundamental parts:

1. PART 1, in which it is defined the number of the constitutive elements of the model (levels, nodes, foundations, panels, openings, slabs etc) and the number of the structural components type in the libraries (type of foundations, type of masonries, type of openings, type of slabs etc);
2. PART 2, which contains 2 groups of variables: the first regards the definition of the regulatory framework, the second regards the localization of the site and the definition of seismic action. At the current state of the proposed procedure these values are considered fixed in all .TXT files being not dependent on the input parameters.
3. PART 3, which required the definition of the geometry of the structural model by means of interstorey height and coordinates of the nodes in a global reference system and the geometrical and mechanical characteristics of the structural elements type derived directly by the input parameters.

All the .TXT files are automatically generated and divided in n_{MUR} x n_{AGG} folders (named MUR0n_{MUR}_AGG0n_{AGG}) relative to the n_{MUR} masonry CARTIS typology and n_{AGG} aggregate configurations.

STEP 2. the files .TXT of the numerical models are imported into POR2000 in succession and the pushover analyses are performed, obtaining N_{TOTAL} outputs files in .OUT format. In general, it is possible to obtain two different output data: the ratio C/D of capacity and demand expressed in term of PGA relative to the 4 limit states, or the bilinear curves defined trough F_y, d_y and d_u for 8 directions of analysis and 2 different horizontal forces distributions. The use of POR2000 allows to implement the analysis and to obtain the output file in a time of about 3 second per models, requiring a low computational effort. The code imports in succession the N_{TOTAL} output files, reads the C/D values relative to the 4 limit states or F_y, d_y, μ (calculate as d_u/d_y) values, allocating in a matrices (.MAT file), for each direction of analysis and type of distribution.

STEP 3. for each CARTIS typology MUR0n_{MUR} and aggregate configuration AGG0n_{AGG}, it is implemented the sensitivity analysis calculating first order index S_i, total effect index S_{Ti}, and Tornado analysis diagram TDA to estimate and identify the P_S most influence input parameter on the variability of each output parameter;

STEP 4. Clusterization is carried out by grouping the models of the sample with equal value of the $X_{Ps,i}$ input parameter. The mean value of each output parameter is calculated for each cluster.

STEP 5. The mean value of output parameters of the cluster of the single cell and relative aggregate configurations are plotted in the same graph and it is carried out a fit regression analysis. The best fit regression models identified are verified and calibrated considering clusters of some further aggregate configurations and repeating the STEP 1, STEP 2 and STEP 5.

The calibrated regression models allow to predict the structural behaviour of different aggregate configurations starting from knowledge of the single building.

6.6 Application to the case study of Foggia

6.6.1 Description of the case study

The proposed methodology has been applied to a pilot case, the municipality of Foggia, a city located in the north of Puglia, in southern Italy. The CARTIS form have been compiled for the city (Figure 6.6.4); 6 different homogeneous urban sectors have been identified as shown in Figure 6.6.1, with relative CARTIS classes, both for RC and masonry buildings. Most of the CARTIS masonry classes are in the centre of the city divides in urban sector C01, C02 and C03. All the masonry buildings are organized in aggregate with different dimensions and form, as usually in historical centre of the cities.

The procedure has been tested on the urban sector C02 (Figure 6.6.2) in which the masonry buildings are about the 60% of the total (ISTAT, 2011). 2 CARTIS masonry classes are identified: MUR01 and MUR02 with relative general, geometrical, structural and typological characteristics listed in Table 6.6.1.

The recurrent aggregate typology in C02 is the rowhouses composed by a single row of structural units with similar height and area floor, hence, the aggregates have, generally, a rectangular shape with shorter side coincident with one side of single building variable between the range 10-15 m (Figure 6.6.4).

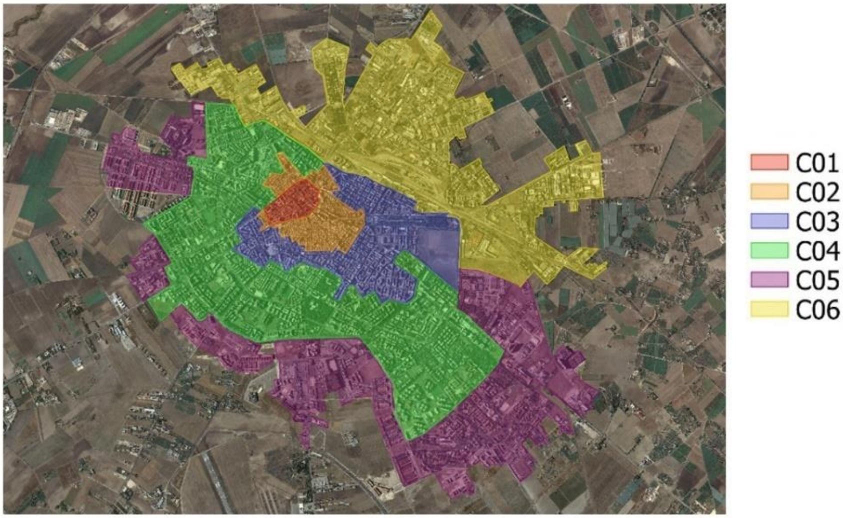


Figure 6.6.1- Urban sectors of Foggia Municipality, through GIS elaboration

Figure 6.6.2 - View of C02 urban sector in the historical centre of Foggia and structural typology identification through CARTIS form

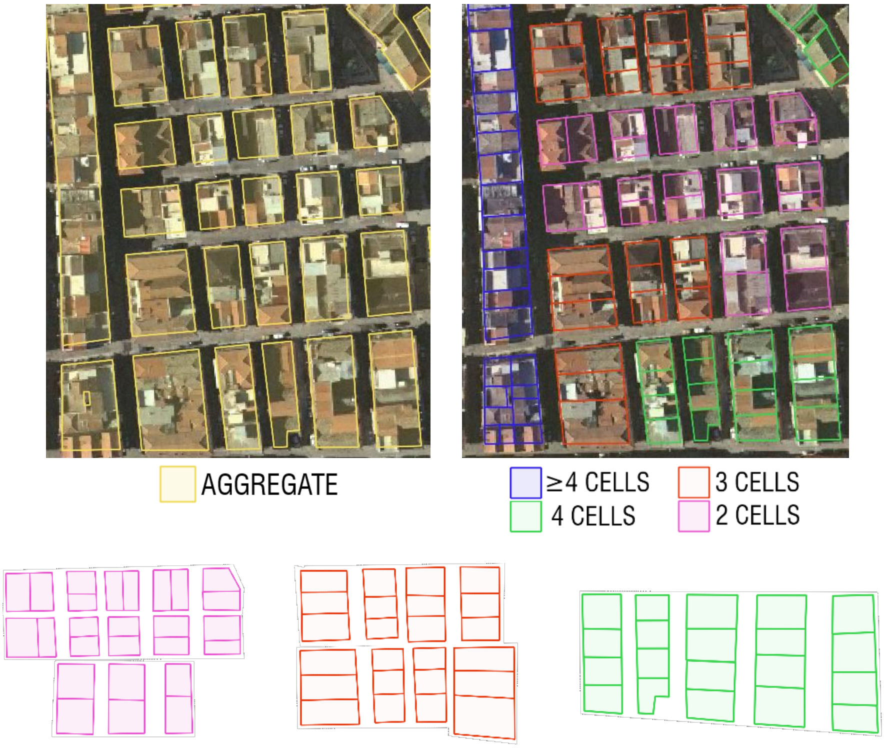


Figure 6.6.3 - Example of the most recurrent masonry building aggregate configurations of the C02 urban sector

Figure 6.6.4 - CARTIS forms of MUR01 and MUR02 classes of the C02 urban sector

Table 6.6.1 - MUR01 and MUR02 characteristics derived by the relative CARTIS forms

DATA	MUR01	MUR02
Age of construction	1861-1919	1861-1919
Number of storeys	1-2	2-3
Mean interstorey height of ground floor [m]	2,50-3,49	2,50-3,49
Mean interstorey height of upper floors [m]	2,50-3,49	2,50-3,49
Mean area floor [m2]	70-100	130-170
Masonry typology	square stone block	square stone block
Mean thickness of wall [cm]	50	50
floor type	Rigid slab	Rigid slab
Roof type	Flat roof	Flat roof
Percentage of openings at ground floor	20-29	20-29
Regularity	In plan a height	In plan a height

6.6.2 Buildings samples generation and analysis

The procedure has been implemented by means of MATLAB code elaborated and described is section 6.5.

The 7 input variables have been assumed for the 7 parameters P_n, listed in Table 6.6.2. Each variable is defined by means of an array containing the $X_{P,i}$ values of the corresponding range extracted from GMSD.

The variable “sideY” contains the values of the width of the aggregates equal to recurrent sizes of the shorter side of the urban blocks in the sector C02 and coincident with a side of the component cells.

In CARTIS forms 2 possible values of area, percentage of openings at the ground floor and at the upper floors have been defined; these values have been assumed as the minimum and maximum and a further intermediate values are considered by dividing the range into equal steps; the values obtained are stored in the arrays corresponding to the variables “area”, “%openI” and “%openS”; the variable “numlev”, relative to the number of storeys parameter, is defined with an array containing the 2 values reported in CARTIS from; 1 value of mean thickness of wall is available in CARTIS form; in this case, further 4 recurrent values in the masonry buildings have been considered obtained 5 total values for the variable “thickwall”.

Minimum and maximum values of mean compressive strength f and tensile strength f_v are derived by the Tab C.8.5.I of the guideline of NTC18 (C.E., 2019), assuming a regular limestone masonry typology, coherently with the age of construction and other specific information reported in CARTIS form. Other 2 intermediate values are assumed by dividing the range into 3 equal steps, obtaining 4 total values for the relative variable “f_c” and “f_v”. The mechanical characterization of the masonry, in absence of experimental data, has been assumed equal to the two correspondent values in the arrays of the variables “f_c” and “f_v”.

Table 6.6.2 - Parameters and relative range of values for each structural-typological classes

n_P	parameter	variable	number of values X_P	range of values	
				MUR01	MUR02
P_1	width	sideY	3	[10 12 15]	
P_2	area	area	3	[70 85 100]	[130 150 170]
P_3	number of storeys	numlev	2	[2 3]	[3 4]
P_4	thickness of wall	thickwall	5	[0.25 0.30 0.50 0.70 1]	
P_5	Percentage of openings upper floor	%openS	3	[10 15 20]	
P_6	Percentage of openings ground floor	%openI	3	[20 25 30]	
P_7	Mean compressive strength Mean compressive strength	f_c f_v	4 value pairs	[20.41 24.49 28.57 32.65] [1.02 1.33 1.63 1.94]	

The single cells have been considered regular in plan, with a square or rectangular shape, and regular in height, with mean interstorey height of 3.5 m for the ground floor and 3 m for the upper floors, moreover, all the masonry panels are considered load-bearing walls. A numerical model N of a cell correspond to a specific N_n numerical combination of the values $X_{P,i}$ of each parameter.

The different aggregate configurations have been constructed by replicating an increasing number of equal numerical model (MODEL N) corresponding to a specific reference cell, according the most recurrent typological aggregate in sector C02; 3 different aggregate configurations have been considered respectively composed by 2, 3 and 4 cells (Figure 6.6.5)

In total 4 configurations have been considered respectively for MUR01 and MUR02: The single cell configuration AGG01 and the 3 aggregate configurations AGG02 (2 cells), AGG03 (3 cells) and AGG04 (4 cells), obtained 8 configurations (Table 6.6.3).

It is possible to generate for each configuration a statistical sample composed by the models equivalent to all the possible numerical combinations N_n of the input variables. In this case, a sample of each configuration is composed by 3240 models obtaining a total number N_{total} of the models obtained equal to 25920.

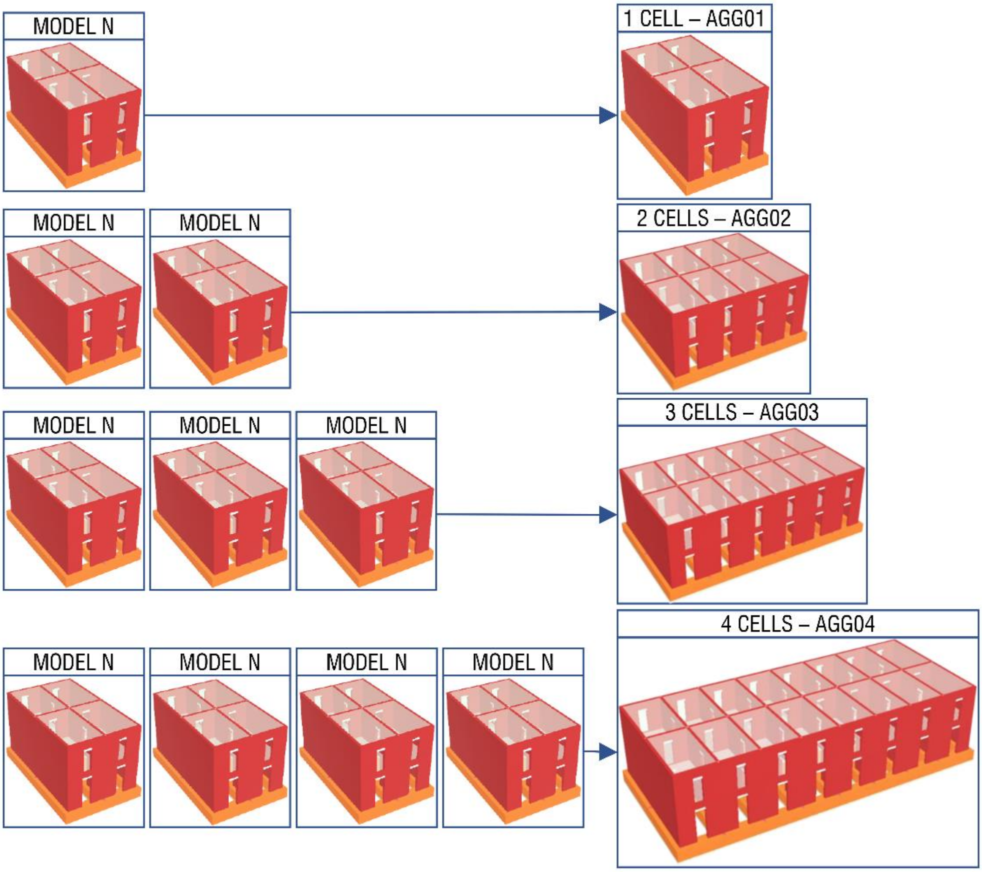


Figure 6.6.5 - example of aggregate configurations obtained starting from a specific numerical model of a sample

Table 6.6.3 - groups of models samples

number of cells	**CARTIS masonry class**	
	MUR01	**MUR02**
1	MUR01 AGG01	MUR02 AGG01
2	MUR01 AGG02	MUR02 AGG02
3	MUR01 AGG03	MUR02 AGG03
4	MUR01 AGG04	MUR02 AGG04

The input variables are used to compile the .TXT files which define the numerical models according to the structure described in section 6.5.
In the part 1, the number of levels is defined using the input variable “numlev”.
The values of the input variable “sideY” defines one side length of the cell along the y direction in the global reference system; the other side length along x direction has been computed dividing input variable “area” by input variable “sideY”, the resulting value has been compared with maximum span length, assumed equal to 6 m (as suggested in CARTIS form), obtaining the number of bays; then, the number of nodes have been obtained by multiplying the number of masonry walls along the 2 sides.
The number of the elements of the libraries of foundations, masonries, openings and slabs is incremented of 1 adding a new editable type.
The parameters in the part 2 of the .TXT file have been defined by means of properly coding, fixed for all numerical combinations, being independent on any input variables. In particular, the Italian Building Code NTC2018 has been assumed as the reference standard; the site has been localized by means of geographical coordinates (longitude and latitude); moreover, the following parameters have been considered: use class 2 (ordinary buildings), soil category A, topographic category T1, return period for SLO 30 years, SLD 50 years, SLV 475 years and SLC 975 years (as suggested in NTC18).
In part 3 has been defined the geometry and the mechanical characteristics of the models: the interstorey height is assumed 3,5 m at the ground floor and 3 m at the upper floors. The coordinates of the nodes are properly defined on the basis of sides length of the cell preciously calculated.
It has been defined the mechanical characteristics by editing each type added in the libraries of the software. The foundations element has been considered in masonry with height 1,00 m, limit load on the soil q_{lim} assumed equal to 4,5 and relative safety factor f_s equal to 2,30, Winkler soil coefficient equal to 5, wet cohesion equal to 0, friction angle of soil equal to 27,0°, and weight of the soil volume unit equal to 1800 kg/m^3; the mechanical characteristics of the limestone masonry typology has been defined as follows: weight of the soil volume equal to 1632 kg/m^3; the values of mean compressive strength f and mean tensile strength f_v have been compiled for each

different numerical combination using the value pairs of the input variables "f_c" and "f_v"; Young modulus E and shear modulus G have been calculated, using the relations given by Italian building code (§11.10.3.4, NTC, 2018), as follow:

$$E = f_c \cdot 1000 \quad (6.6.1)$$

$$G = 0.4 \cdot E \quad (6.6.2)$$

safety factor for nonlinear static analysis γ_M is assumed equal to 1; confidence factor FC is assumed equal to 1 since the uncertainty on mechanical characteristics is assumed by varying the value of mean compressive strength f and mean tensile strength f_v in relative ranges; ductility d is specified for each limit state as the percentage of the height of panel coherently with values d_{sld}, $d_{S,slc}$ and $d_{M,slc}$ listed in section 6.2.

The slab has been considered composed by a concrete masonry floor with RC joists and hollow clay blocks 15 cm high, completed by a RC plate 5 cm thick with a weight of volume unit weight equal to 472 kg/m^3.

The base and height of openings have been calculated for each numerical combination using the values of variables %openI and %openS.

Then the geometry of the model has been constructed by defining position of the masonry panel between 2 subsequent nodes, position of the openings in the local reference system of the panel and position of the slabs defined using 4 nodes.

The code automatically compiles the 8 groups of 3240 .TXT files, which describe the sample of the numerical models, computing all possible numerical combination of the 7 input variables.

The 25920 total numerical combinations of the 7 input variables have been stored in a general matrix of 7x25920 size, useful for the subsequent elaborations.

Pushover analyses have been performed implementing in succession the .TXT files in POR2000 by means of the MATLAB code. The analysis returns 25920 output files .OUT of the bilinear curves of equivalent SDoF system for 8 directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) and 2 distributions of horizontal forces (linear and constant) and 25920 output files .OUT of the C/D ratio relative to the 4 limit states. Then, MATLAB code reads all .OUT file extracting values of the C/D ratio, F_y, d_y and μ.

In this application, the output values F_y, d_y and μ relative to directions 0°, 90° and 45° for constant and linear horizontal distribution loads have been considered and allocated in relative matrix defined as follow:

- Pushover_0_costante
- Pushover_0_lineare
- Pushover_90_costante
- Pushover_90_lineare
- Pushover_45_costante
- Pushover_45_lineare

On the bases of this metrices several type of post-processing can be carried out.
Firstly, it has been evaluated the range of the output F_y, d_y and μ by plotting the bilinear curves.
The whole sample composed by 25920 models (Figure 6.6.6 - bilinear curves plot of 0° direction and constant horizontal forces distribution of the total sample; b) sample of MUR01 class; c) sample of MUR02 class (Figure 6.6.6) and the samples of each structural-typological class MUR01 and MUR02, obtained by splitting the whole sample, (Figure 6.6.7), show a wide range of F_y, d_y and μ.
Consequently, the samples have been reduced considering each of the 8 MUR0n AGG0n configurations; the relative groups of bilinear curves are shown in as showed is the Figure 6.6.6, Figure 6.6.7 and Figure 6.6.8**Errore. L'origine riferimento non è stata trovata.** and, also in this case, the outputs range of values, listed in Table 6.6.4, are still too large. This mean that the sample analysed are composed by models with significantly different seismic response.

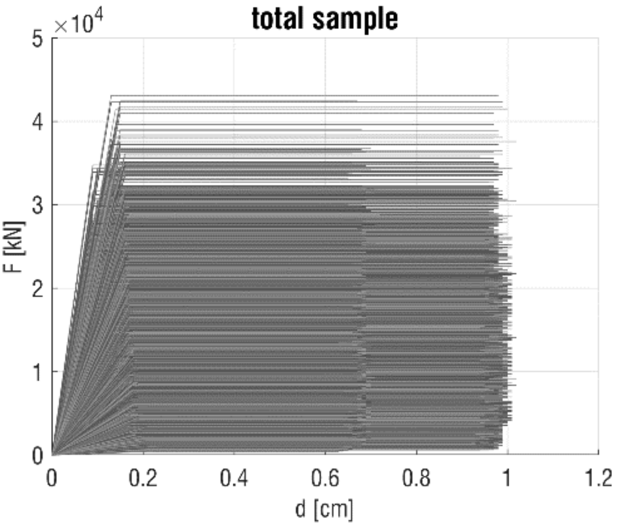


Figure 6.6.6 - bilinear curves plot of 0° direction and constant horizontal forces distribution of the total sample; b) sample of MUR01 class; c) sample of MUR02 class

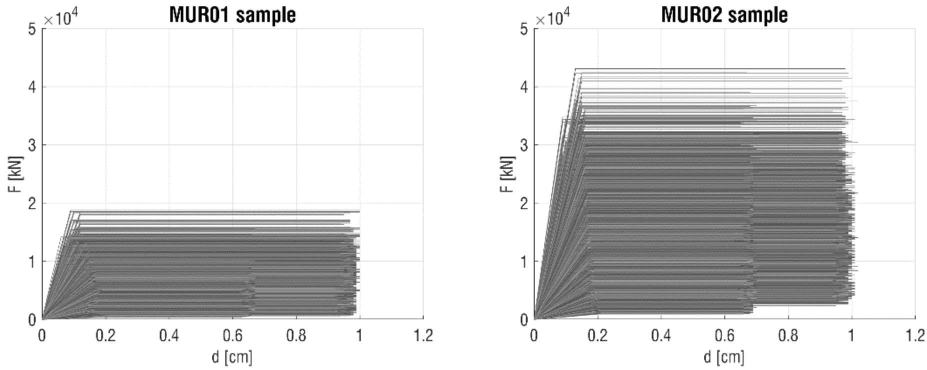


Figure 6.6.7 - bilinear curves plot of 0° direction and constant horizontal forces distribution of the MUR01 sample and MUR02 sample

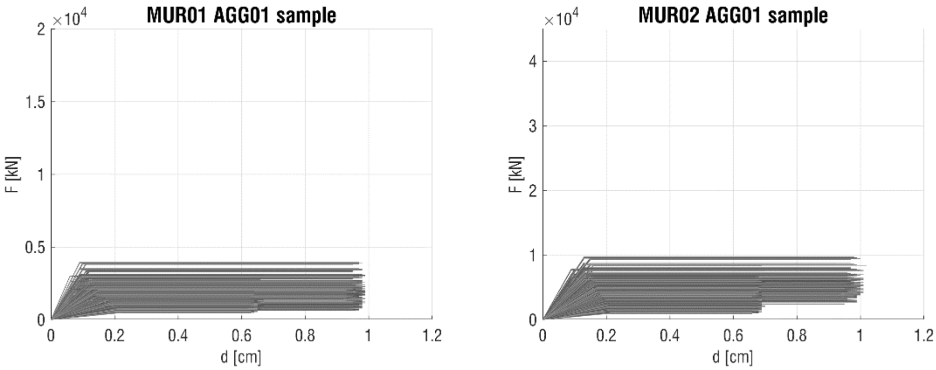


Figure 6.6.8a - bilinear curves plot of 0° direction and constant horizontal forces distribution of the samples of MUR01 AGG01 and MUR02 AGG01

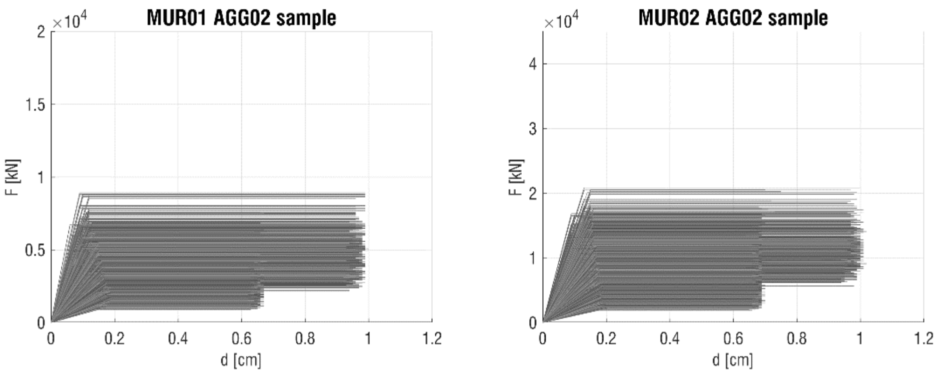


Figure 6.6.8b - bilinear curves plot of 0° direction and constant horizontal forces distribution of the samples of MUR01 AGG02 and MUR02 AGG02

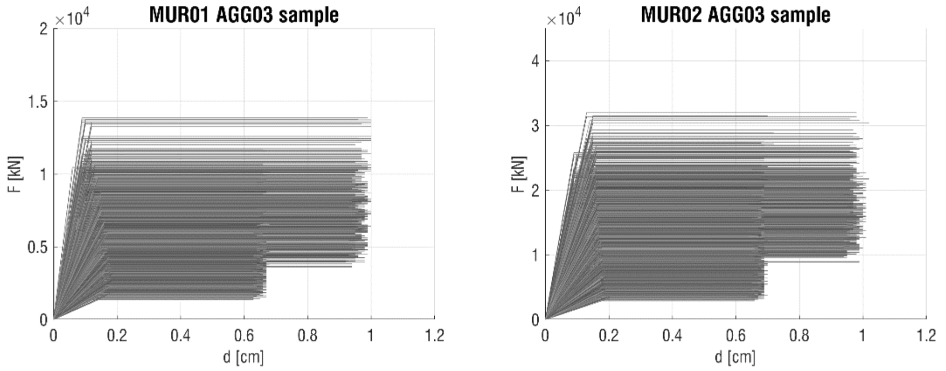


Figure 6.6.8c - bilinear curves plot of 0° direction and constant horizontal forces distribution of the samples of MUR01 AGG03 and MUR02 AGG03

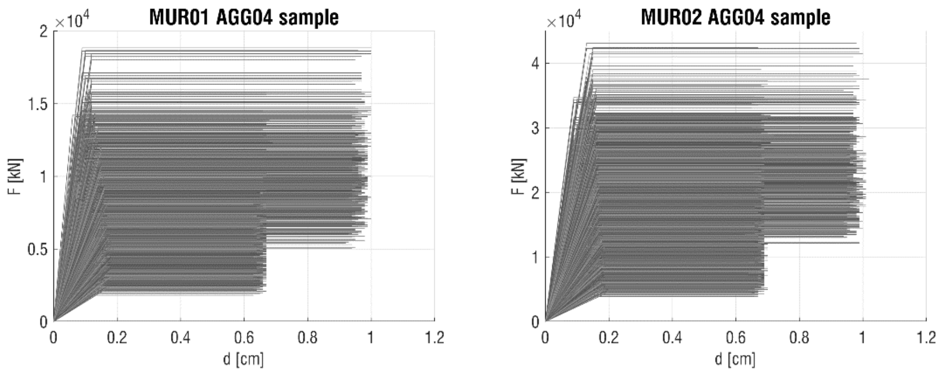


Figure 6.6.8d - bilinear curves plot of 0° direction and constant horizontal forces distribution of the samples of a) MUR01 AGG04 and MUR02 AGG04

Table 6.6.4 - values ranges of F_y, d_y and μ of the different models samples

Sample	F_y [kN] [min ÷ max] variation	d_y [cm] [min ÷ max] variation	μ [min ÷ max] variation
TOTAL SAMPLE	[449,61÷ 43085,56]	[0,06 ÷ 0,26]	[2,42 ÷ 16,67]
	42635,95	0,20	14,24
MUR01	[449,61 ÷ 18828,44]	[0,06 ÷ 0,26]	[2,42 ÷ 16,67]
	18378,83	0,20	14,24
MUR02	[945,72 ÷ 43085,56]	[0,09 0,24]	[2,79 ÷ 11,11]
	42139,84	0,15	8,32
MUR01_AGG01	[449,61 ÷ 3949,92]	[0,06 ÷ 0,26]	[2,42 ÷ 16,50]
	3500,31	0,20	14,08
MUR01_AGG02	[903,40 ÷ 8909,45]	[0,06 ÷ 0,19]	[3,32 ÷ 16,50]
	8006,05	0,13	13,18
MUR01_AGG03	[1360,77 ÷ 13868,98]	[0,06 ÷ 0,19]	[3,312 ÷ 16,50]
	12508,21	0,13	13,18
MUR01_AGG04	[1818,80 ÷ 18828,44]	[0,06 ÷ 0,19]	[3,316 ÷ 16,67]
	17009,64	0,13	13,35
MUR02_AGG01	[945,72 ÷ 9727,91]	[0,09 ÷ 0,24]	[2,79 ÷ 11,11]
	8782,19	0,15	8,32
MUR02_AGG02	[1917,38 ÷ 20847,30]	[0,09 ÷ 0,22]	[3,05 ÷ 11,11]
	18929,92	0,13	8,06
MUR02_AGG03	[2889,33 ÷ 31966,45]	[0,09 ÷ 0,21]	[3,14 ÷ 11,11]
	29077,12	0,12	7,96
MUR02_AGG04	[3861,52 ÷ 43085,56]	[0,09 ÷ 0,21]	[3,19 ÷ 11,11]
	39224,04	0,12	7,92

6.6.3 Sensitivity analysis and clusterization of the samples

The results of the previously analyses indicate that it must be made a further splitting of the samples to reduce the range of values of the output variables F_y, d_y and μ, grouping together the models with a similar seismic behaviour. Hence, it is necessary to identify which of the 7 input variables have more influence on the ranges of the output variables F_y, d_y and μ. The sensitivity analysis is carried out for this purpose according to the procedures described in section 6.4.

The first order sensitivity index S_i total effect sensitivity index S_{Ti} have been evaluated and TDA have been performed for the 8 configurations considering the output of push-over analyses in 0°, 45°, 90° directions, constant and linear horizontal forces distributions.

The S_i and S_{Ti} indices, based on a probabilistic approach, have been calculated by assuming a uniform probabilistic distribution for the input parameters.

The two indices S_i and S_{Ti} show, in most of the cases, a same trend for the different configurations.

The outputs F_y, d_y and μ have been analysed for the constant horizontal force distribution applied in 0° direction along which the piers grow in length and not in number by increasing the number of cells in aggregate configurations (Figure 6.6.9).

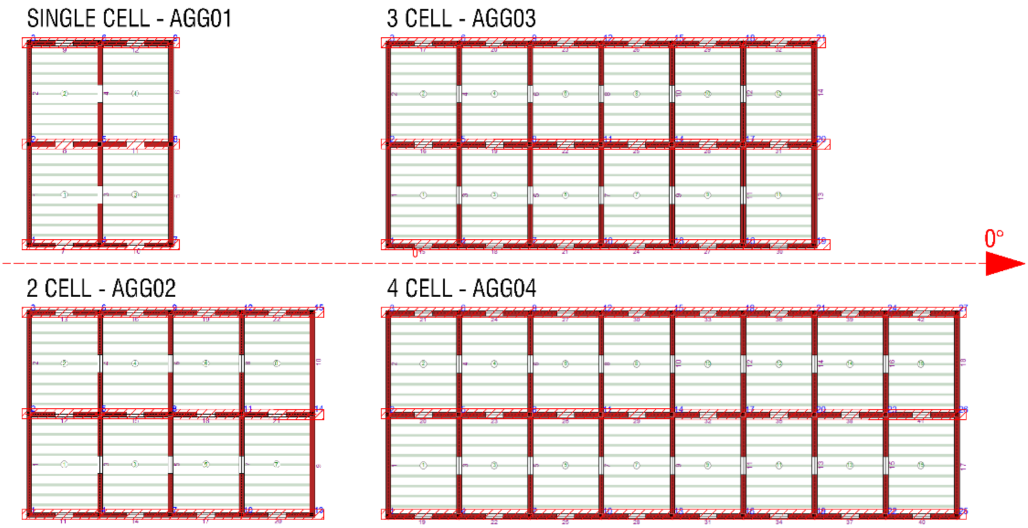


Figure 6.6.9 - length of piers along 0° direction in the different configurations

The output F_y (Figure 6.6.10) show high sensitivity to the thickness of wall (thickwall) and medium sensitivity to the mean compressive strength f_c (f_c), percentage of openings at ground floor (%openl) and number of storeys (numlev); the output d_y (Figure 6.6.11) have high sensitivity to the number of storeys (numlev), thickness of wall (thickwall) and compressive strength f_c (f_c); the output μ (Figure 6.6.12) have high sensitivity to thickness of wall (thickwall), number of storeys (numlev) and compressive strength f_c (f_c). The other input variables have been considered negligible in variability of output, having very low S_i and S_{Ti} values.

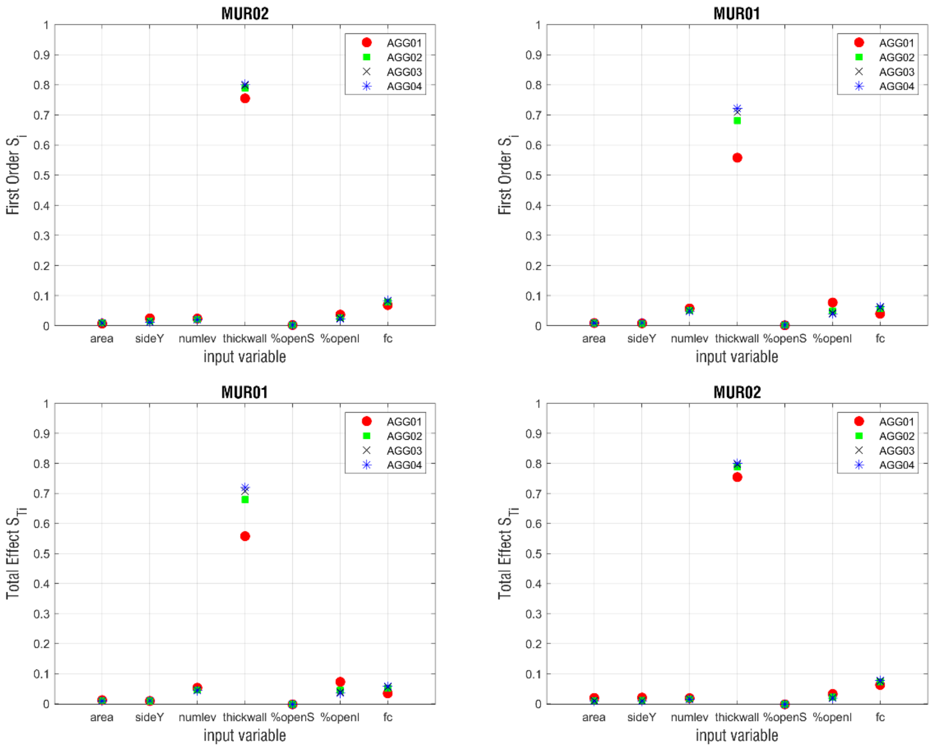


Figure 6.6.10 - F_y, first order index S_i and Total effect index S_{Ti} of the aggregate configurations of the MUR01 and MUR02, pushover analyses 0° direction, constant horizontal forces distribution

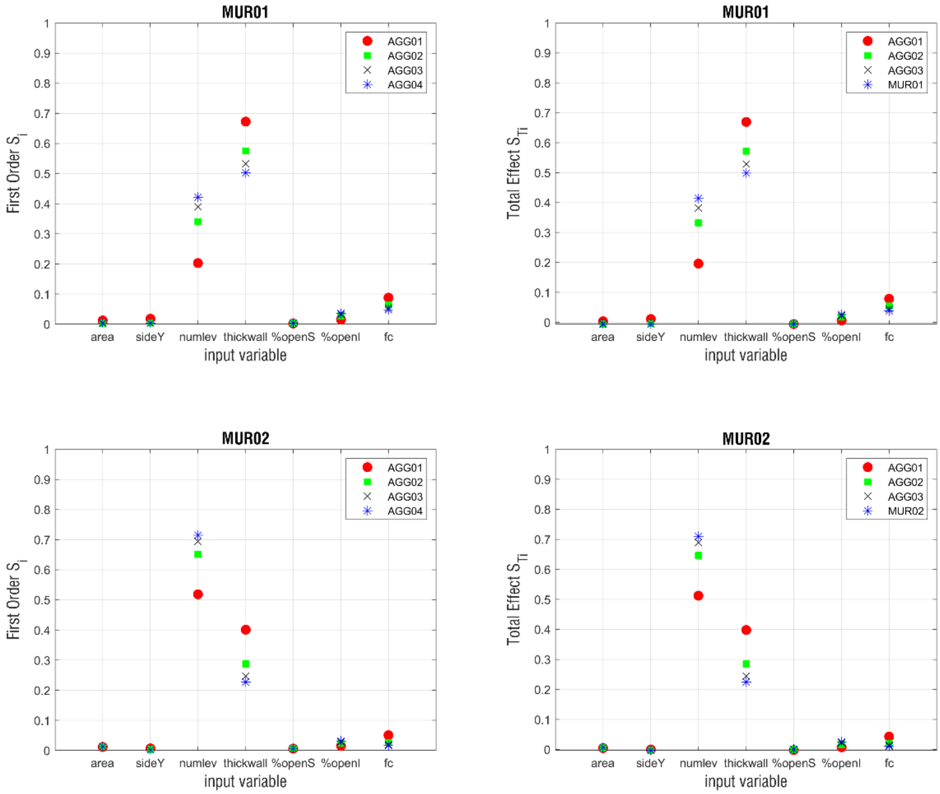


Figure 6.6.11 - dy, first order index S_i and Total effect index S_{Ti} of the aggregate configurations of the MUR01 and MUR02, pushover analyses 0° direction, constant horizontal forces distribution

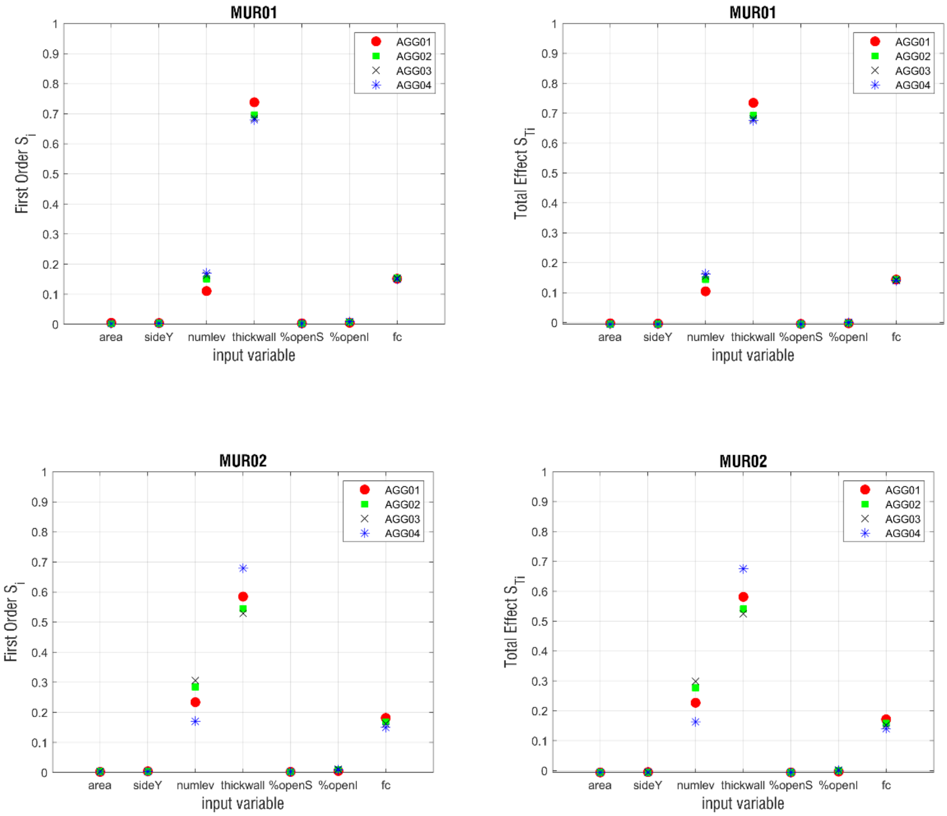


Figure 6.6.12 - μ, first order index S_i and Total effect index S_{Ti} of the aggregate configurations of the MUR01 and MUR02, pushover analyses 0° direction, constant horizontal forces distribution

Table 6.6.5 - identification of most influence input parameters on the variability of the output parameters F_y, d_y and μ, pushover analyses 0° direction, constant horizontal forces distribution

Input variable	MUR01 class						MUR02 class					
	first order S_i			total effect S_{Ti}			first order S_i			total effect S_{Ti}		
	F_y	d_y	μ	F_y	d_y	μ	F_y	d_y	μ	F_y	d_y	μ
sideY												
area												
numlev	x	x	x	x	x	x	x	x	x	x	x	x
thickwall	x	x	x	x	x	x	x	x	x	x	x	x
%openS												
%openI	x			x			x			x		
f_c	x	x	x	x	x	x	x	x	x	x	x	x

The Tornado Diagram Analysis (TDA) have been implemented assuming the inputs and outputs as deterministic variables. At first, the 7 input variables have been simultaneously imposed equal to central value X_P of the ranges, assumed as mean value, obtaining a specific numerical combination; the correspondent model has been extracted from the sample, and the correspondent values of F_y, d_y, and μ are assumed as mean values $F_{y,mean}$, $d_{y,mean}$ and μ_{mean} of the outputs (Table 6.6.6). Subsequently, minimum and maximum value of the range has been considered for one input variables at time, fixing the other input variables equal to their mean value (

Table 6.6.7); relative F_y, d_y, and μ have been assumed as minimum values $F_{y,min}$ $d_{y,min}$ and μ_{min} and maximum values $F_{y,max}$ $d_{y,max}$ and μ_{max}.

The value of outputs have been normalize with respect $F_{y,mean}$, $d_{y,mean}$ and μ_{mean} obtaining the percentage variation. The difference between the normalized value of $F_{y,max}$ $d_{y,max}$ and μ_{max} and $F_{y,min}$ $d_{y,min}$ and μ_m corresponds to the swing value SV which represents the percentage variation of the output due to the variation of each single input variable. A high value of SV implies a high sensitivity of the output variables F_y, d_y, and μ_{max} to the variation of the input variable.

The results are plotted in the tornado diagram: for each input variable is represented a bar with length proportional to SV in decreasing order.

The results of TDA, in accord with S_i and S_{Ti}, show that, the higher variations of F_y, dy and μ output values (Figure 6.6.13, Figure 6.6.14, Figure 6.6.15) are due to the thickness of wall (thickwall), mean compressive strength f_c (f_c), percentage of openings at ground floor (%openI) and number of storeys (numlev).

It is possible to deduce further important consideration from the TDA: the 4 configurations of the MUR02 class show a decreasing yielding force F_y due to the increase in the percentage of openings at the ground floor; the 4 configurations of the MUR01 class have a decreasing yielding displacement d_y due to the increase in the mean compressive strength f_c; all the 8 configurations have a decreasing yielding displacement d_y due to the increase in the thickness of wall and a decrease in ductility μ due to the increase of number of the storeys.

Table 6.6.6 - Numerical combination of the mean values of the input variables and relative $F_{y,mean}$, $d_{y,mean}$ and μ_{mean} of the MUR01 class

MUR01 AGG01									
area	**sideY**	**numlev**	**thickwall**	**openS**	**openI**	**f_c**	**$F_{y,mean}$**	**$d_{y,mean}$**	**μ_{mean}**
85	12	2	0.5	15	25	24.49	1144.01	0,13	4.92

Table 6.6.7 - Numerical combination of the mean values of the input variables and relative $F_{y,mean}$, $d_{y,mean}$ and μ_{mean} of the MUR02 class

MUR02 AGG01									
area	**sideY**	**numlev**	**thickwall**	**openS**	**openI**	**f_c**	**$F_{y,mean}$**	**$d_{y,mean}$**	**μ_{mean}**
150	12	2	0.5	15	25	24.49	2603.08	0,15	4,40

Table 6.6.8 - Numerical combinations obtained by varying minimum and maximum one input variables at time and relative F_y, d_y, and μ of the MUR01 and MUR02 class

MUR01 AGG01								
		area	**sideY**	**numlev**	**thickwall**	**openS**	**openI**	**f_c**
01	**min**	**70**	12	2	0.5	15	25	24.49
01	**max**	**100**	12	2	0.5	15	25	24.49
02	**min**	85	**10**	2	0.5	15	25	24.49
02	**max**	85	**15**	2	0.5	15	25	24.49
03	**min**	85	12	**2**	0.5	15	25	24.49
03	**max**	85	12	**3**	0.5	15	25	24.49
04	**min**	85	12	2	**0.25**	15	25	24.49
04	**max**	85	12	2	**1.00**	15	25	24.49
05	**min**	85	12	2	0.5	**10**	25	24.49
05	**max**	85	12	2	0.5	**20**	25	24.49
06	**min**	85	12	2	0.5	15	**20**	24.49
06	**max**	85	12	2	0.5	15	**30**	24.49
07	**min**	85	12	2	0.5	15	25	**20.41**
07	**max**	85	12	2	0.5	15	25	**32.62**

Table 6.6.9 - Numerical combinations obtained by varying minimum and maximum one input variables at time and relative F_y, d_y, and μ of the MUR02 class

MUR02 AGG01								
		area	**sideY**	**numlev**	**thickwall**	**openS**	**openI**	**f_c**
01	**min**	**130**	12	3	0.5	15	25	24.49
01	**max**	**170**	12	3	0.5	15	25	24.49
02	**min**	150	**10**	3	0.5	15	25	24.49
02	**max**	150	**15**	3	0.5	15	25	24.49
03	**min**	150	12	**3**	0.5	15	25	24.49
03	**max**	150	12	**4**	0.5	15	25	24.49
04	**min**	150	12	3	**0.25**	15	25	24.49
04	**max**	150	12	3	**1.00**	15	25	24.49
05	**min**	150	12	3	0.5	**10**	25	24.49
05	**max**	150	12	3	0.5	**20**	25	24.49
06	**min**	150	12	3	0.5	15	**20**	24.49
06	**max**	150	12	3	0.5	15	**30**	24.49
07	**min**	150	12	3	0.5	15	25	**20.41**
07	**max**	150	12	3	0.5	15	25	**32.62**

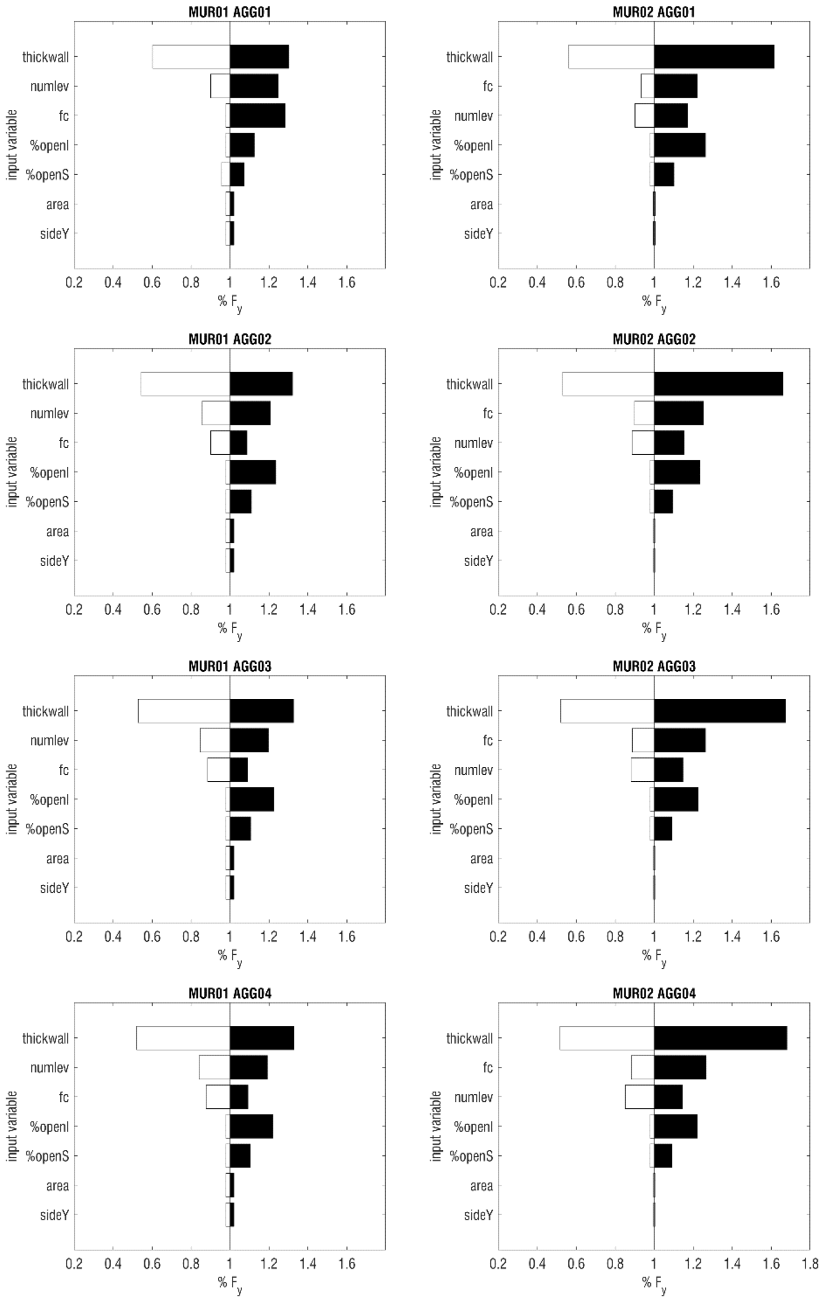


Figure 6.6.13 - F_y Tornado Diagram for the different aggregate configuration of MUR01 sample and MUR02 sample; pushover analyses 0° direction and constant horizontal forces distribution

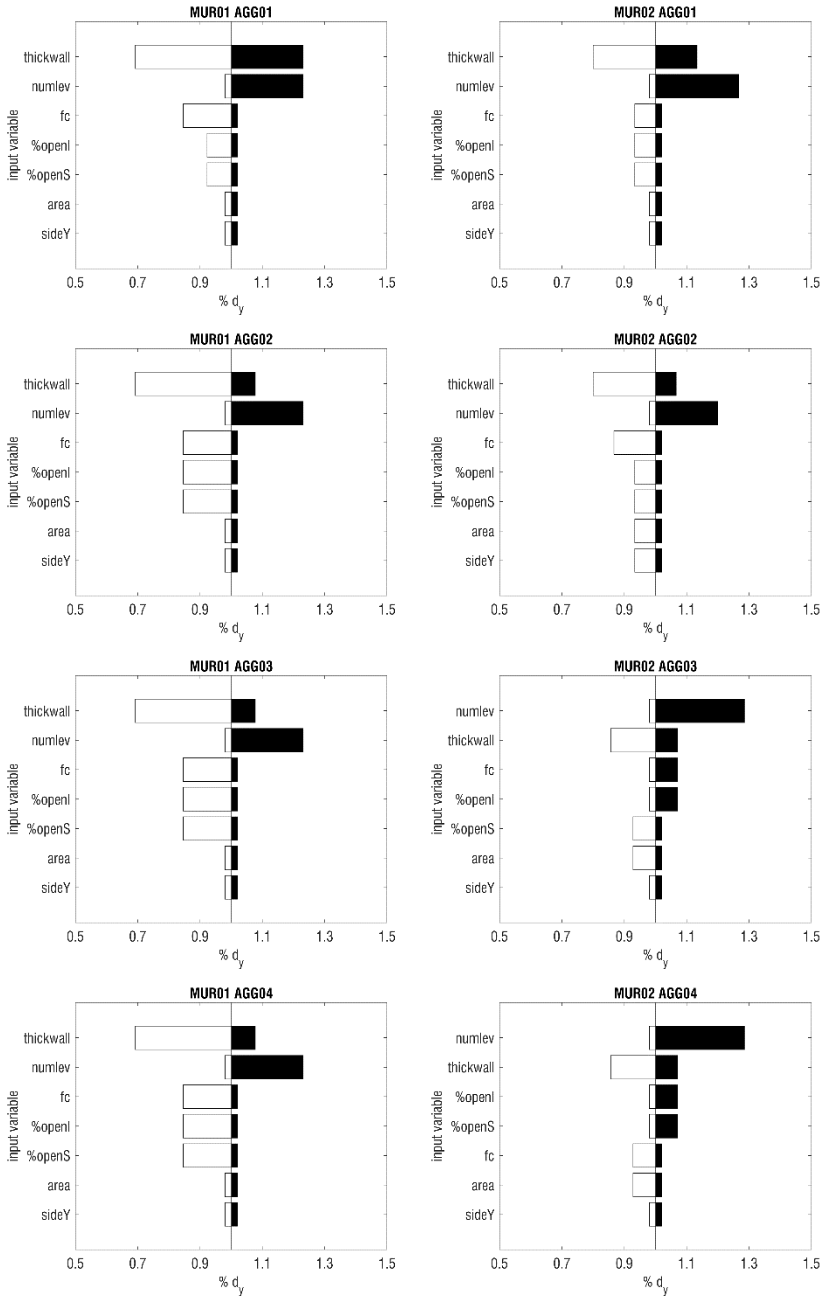


Figure 6.6.14 - d_y Tornado Diagram for the different aggregate configuration of MUR01 sample and MUR02 sample; pushover analyses 0° direction and constant horizontal forces distribution

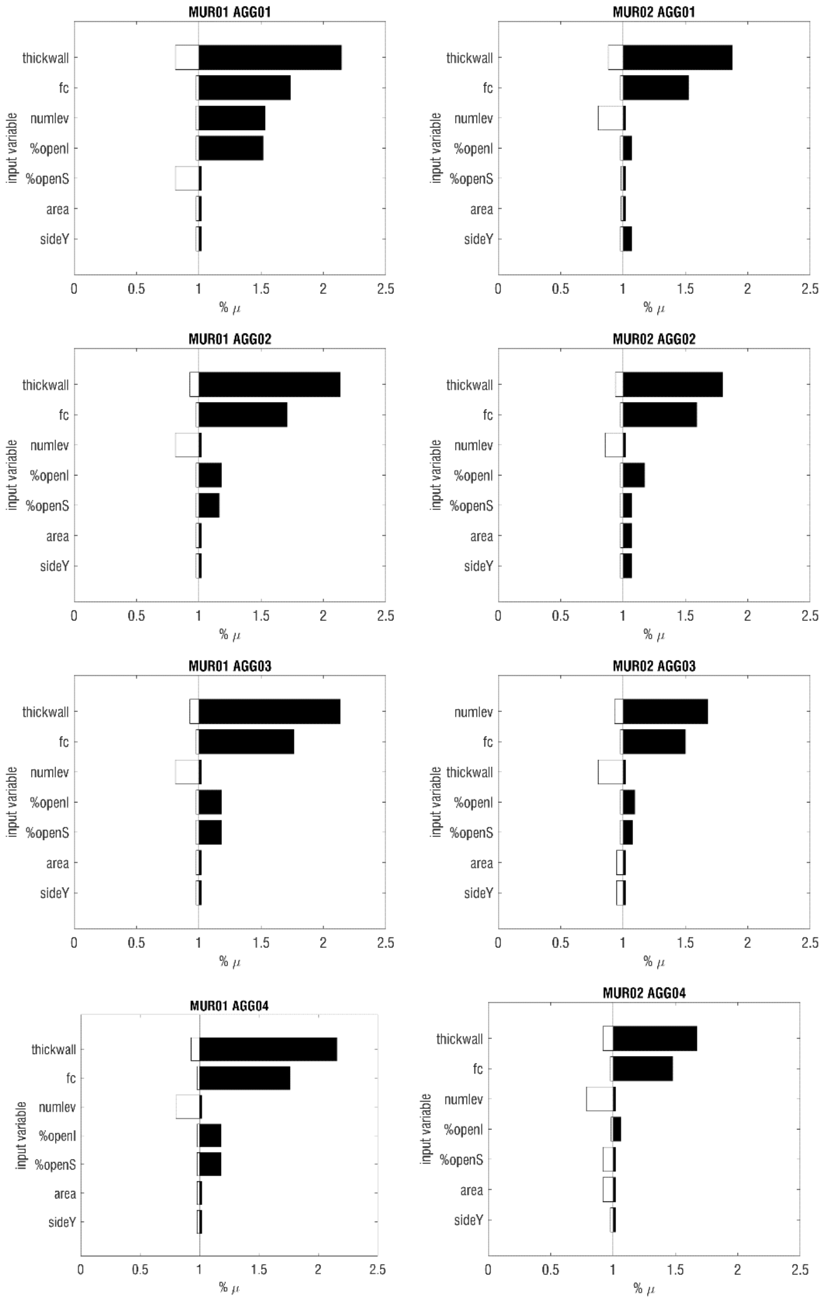


Figure 6.6.15 - μ Tornado Diagram of the different aggregate configuration of MUR01 sample and MUR02 SAMPLE, pushover analyses 0° direction, constant horizontal forces distribution

The results of the sensitivity analysis show that the variability of the output variables F_y, d_y and μ have high sensitivity to the following impute parameters P_s:

- P_3 number of storeys, “numlev”;
- P_4 thickness of wall, “thickwall”;
- P_6 Percentage of open at the ground floor, “%openl”;
- P_7 f_c, “f_c”;

A properly clusterization of the model samples allows to reduce the range of the values of the output variables F_y, d_y and μ. The clusters must be grouping all the models corresponding to the numerical combinations with equal values of the most influent input parameters P_3, P_4, P_6, P_7.

In this case, 120 clusters composed by 27 models have been obtained for each configuration, AGG01, AGG02, AGG03 and AGG04 of the same CARTIS class MUR01and MUR02.

Each of the 120 clusters of the single cell configuration AGG01 has a corresponding cluster of aggregate configurations AGG02, AGG03 and AGG04.

The Regression analyses has been performed considering the mean values of the output variables F_y, d_y and μ of a specific single cell configuration cluster and of the corresponding aggregate configurations clusters. The best regression model represents the relation between the output parameters F_y, d_y and μ which defined the structural and seismic behaviour of the single cell configuration and aggregate configurations; in Figure 6.6.16 the mean values of the output variables F_y, d_y and μ are plotted assuming a linear regression model: it is evident that there is a remarkable variability of the trends, hence, the identification of the best regression models must be conducted separately for each groups of clusters.

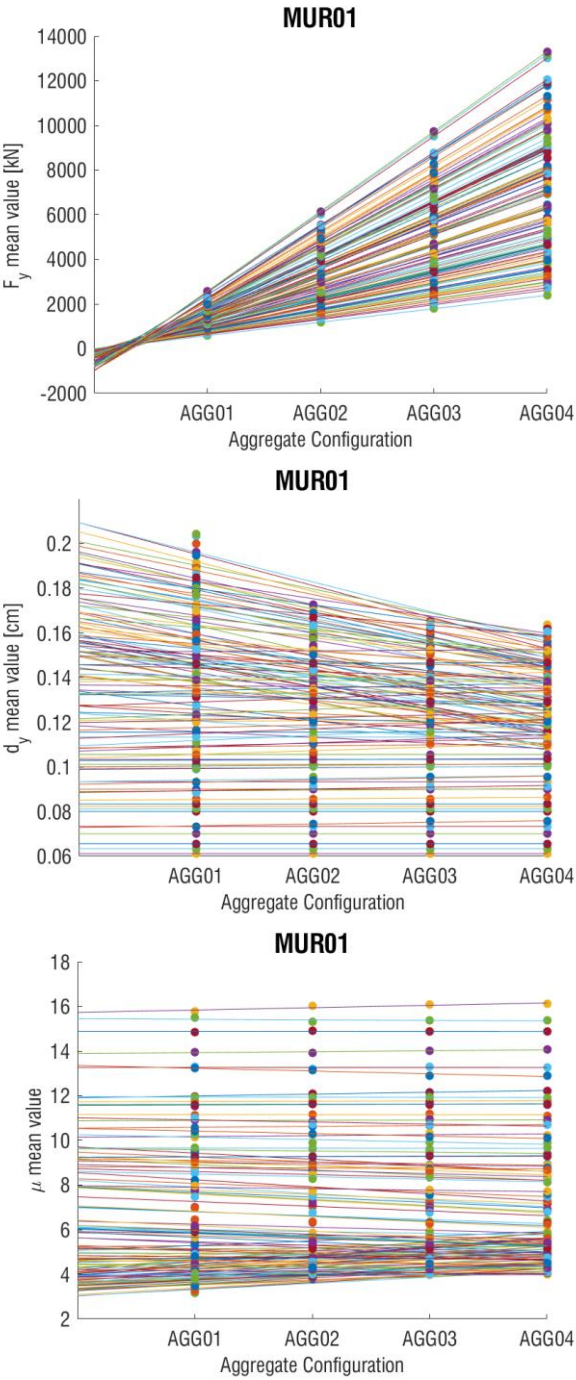


Figure 6.6.16 - Linear Regression between the F_y, d_y, and μ mean values of the 4 aggregate configurations of all the 120 clusters, for the case of 0° direction and constant horizontal distribution force

The specific corresponding clusters for the different configurations in the MUR01 class have been analysed. The cluster considered are the following:

- CLASTER 1-120-240-361: minimum values of the P_S input parameters;
- CLUSTER 3-123-243-363: in which there are the models with minimum value of F_y;
- CLUSTER 29-149-269-389: medium values of the P_S input parameters;
- CLUSTER 58-178-298-418: maximum values of the thickness of wall (thick-wall) and mean compressive strength (f_c) and minimum value of the number of storeys (numlev) and percentage of openings at the ground floor (%openl), for which it is expected structural systems with highest total stiffnesses k;
- CLUSTER 63-183-303-423: minimum values of the thickness of wall (thick-wall) and mean compressive strength (f_c) and maximum values of the number of storeys (numlev) and percentage of openings at the ground floor (%openl), for which it is expected structural systems with lowest total stiffnesses k;
- CLUSTER 66-186-306-426: in which there are the models with maximum value of d_y and minimum value of μ;
- CLUSTER 118-238-358-478: in which there are the models with maximum values of F_y;
- CLASTER 120-240-360-480: maximum values of the P_S input parameters.

In Table 6.6.10 the numerical combinations are listed, correspondent to the models falling in the considering cluster.

Table 6.6.10 - cluster analysed

INPUT VARIABLE		CLUSTER							
		1 120 240 361	**3 123 243 363**	**29 149 269 389**	**58 178 298 418**	**63 183 303 423**	**66 186 306 426**	**118 238 358 478**	**120 240 360 480**
P_1	sideY	[10 12 15]							
P_2	area	[70 85 100]							
P_3	numlev	[2]	[2]	[2]	[2]	[3]	[3]	[3]	[3]
P_4	thickwall	[0,25]	[0,25]	[0,50]	[1,00]	[0,25]	[0,25]	[1,00]	[1,00]
P_5	%openS	[10 15 20]							
P_6	%openI	[20]	[30]	[25]	[20]	[30]	[30]	[20]	[30]
P_7	f_c	[20,41]	[20,41]	[24,49]	[32,65]	[20,41]	[24,49]	[32,65]	[32,65]
	f_V	[1,02]	[1,02]	[1,33]	[1,94]	[1,02]	[1,33]	[1,94]	[1,94]

6.6.4 Results and discussion

The analysis of the F_y mean values trends has been performed at first for the 4 corresponding clusters of the single cell and relative aggregate configurations composed by 2, 3 and 4 cells.

F_y mean values show for all the clusters a linearly increasing and continue to have the same trend considering further aggregate configurations with growing number of cells: 5 cells, 6 cells, 7 cells, 8 cells, 9 cells and 10 cells, as shown in Figure 6.6.17. The increment of the mean F_y values from the single cell configuration to 10 cells configurations is more marked for the clusters which contain the models with highest mean compressive strength f_c and thickness of walls (CLASTER 58, 118, 120 and relative clusters the aggregate configurations), as shown in Figure 6.6.18.

A polynomial regression model described by the Eq. 6.6.3, better fitted the trend of the F_y mean values. The coefficients and the parameters of goodness of fit are listed in Table 6.6.11 for all the groups of clusters analysed.

Instead, the trend of the mean values of the yielding displacement d_y of the first 4 configurations is not strictly linear and show a decreasing trend for the CLUSTER 1, 3, 29, 63 and 66, for which mean F_y values are lower, constant trend for the CLUSTER 58, and increasing trend for CLUSTER 118 and 120, for which mean F_y values are higher. In particular, for the clusters which grouped models with minimum and medium value

of thickness of wall and mean compressive strength f_c, d_y decreases with the number of cells, instead, for the clusters which grouped models with maximum value of thickness of wall and mean compressive strength f_c, d_y increases with the number of cells. The mean value of d_y assumes a constant trend considering further aggregate configurations with 5, 6, 7, 8, 9 and 10 cells for all the clusters analysed. This mean that the effect in terms of yielding displacement is significant passing by the single cell to aggregate configurations until 4 cells and negligible for the aggregate configurations with a growing number of cells Figure 6.6.19.
The best regression model for all the cases is descripted by means of Eq. 6.6.4, except the cluster 58 which has a constant trend. The coefficients and the parameters of goodness of fit are listed in Table 6.6.12 for all the groups of clusters analysed.
A cross-analysis of the trend of mean F_y values and mean d_y values shows that, the CLUSTER 1, 3, 29, 63 and 66 of the single cells models (and relative clusters of the aggregate configurations) have lower mean F_y values and decreasing trend of mean d_y values, instead, the CLUSTER 118 and 120 of the single cells models (and relative clusters of the aggregate configurations) have higher mean F_y values and increasing trend the yielding displacement d_y. the CLUSTER 58 of the single cells models (and relative clusters of the aggregate configurations) which show an intermediate behaviour in terms of F_y values, have a constant trend of mean d_y values.
This have implications in term of total stiffness of the aggregate configurations: as shown in Figure 6.6.21, for all the clusters the mean values of the total stiffness k grow linearly with the number of cells in aggregate configuration and have lower values for clusters that grouped models with minimum and medium value of thickness of walls and mean compressive strength (CLUSTER 1, 3, 29, 63 and 66 of the single cells models and relative clusters of the aggregate configurations), and higher values for the clusters which grouped models with maximum value of thickness of wall and mean compressive strength (118 and 120 of the single cells models and relative clusters of the aggregate configurations). As expected, the CLUSTER 58 and relative clusters of the aggregate configurations have highest value of total stiffness k, instead, the CLUSTER 63 and relative clusters of the aggregate configuration have lowest values of F_y.

The regression models have been defined also for the trend of the k values of each cluster according the Eq. 6.6.5, the coefficient and parameters are listed in Table 6.6.13.

The results confirm the development of “aggregate effect” in terms of total stiffness k of the structural system with growing number of the structural units in the aggregate configurations.

The mean μ values trend of the first 4 configurations of the cluster analysed for all the analysed clusters have a reverse trend compared to that of d_y, indeed, CLUSTER 1, 3, 29, 63 and 66, have a decreasing trend, instead, CLUSTER 58, 118 and 120 have an increasing trend. Moreover, also in this case the trends are not strictly linear and the verification by means of the further aggregate configurations with a growing number of cells, shows that the mean value of μ assumes a constant value by increasing the number of cells (Figure 6.6.22). The “aggregate effect” in term of ductility μ of the structural systems involves a growing values of the ultimate displacement d_u with the number of cells in aggregate configuration until 4 units for the structural system with minimum and medium values of thickness of walls and mean compressive strength (CLUSTER 1, 3, 29, 63 and 66), and decreasing values of d_u for the clusters (CLUSTER 58, 118 and 120) with maximum values of thickness of walls and mean compressive strength, the effect in terms of μ is negligible for number of cells in aggregate configuration greater than 4. The best regression is descripted by custom model according the Eq. 6.6.6 and the coefficients and parameters of goodness of fit are listed in Table 6.6.14.

The regression models defined represent the “aggregations rules” for the analysed clusters, allowing to predict the structural and seismic behaviour of the aggregate configurations in terms of mean values F_y, d_y and μ and total stiffness k by defining few geometrical, structural and mechanical characteristics of the single structural units.

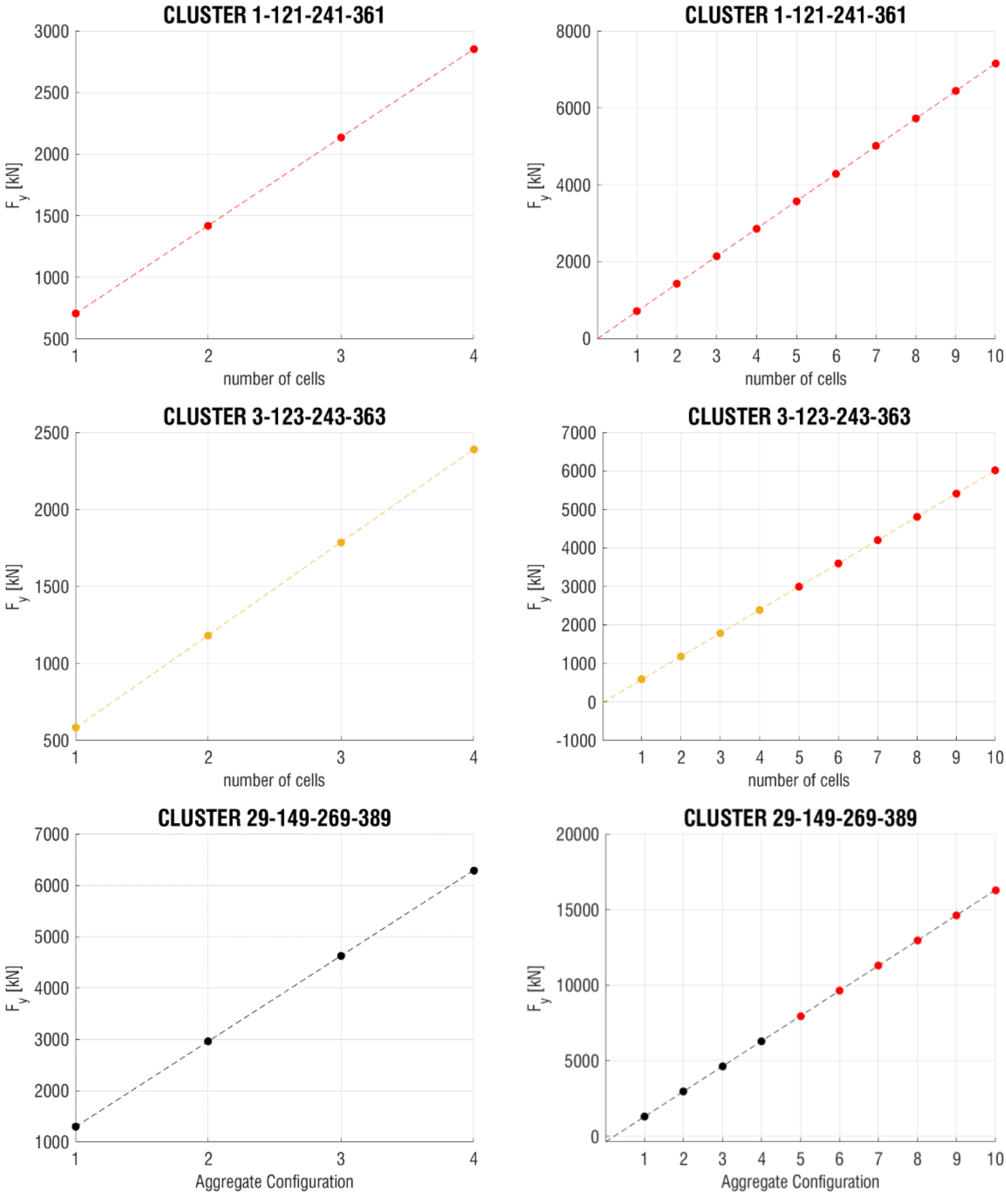


Figure 6.6.17 - linear regression of mean values of F_y of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

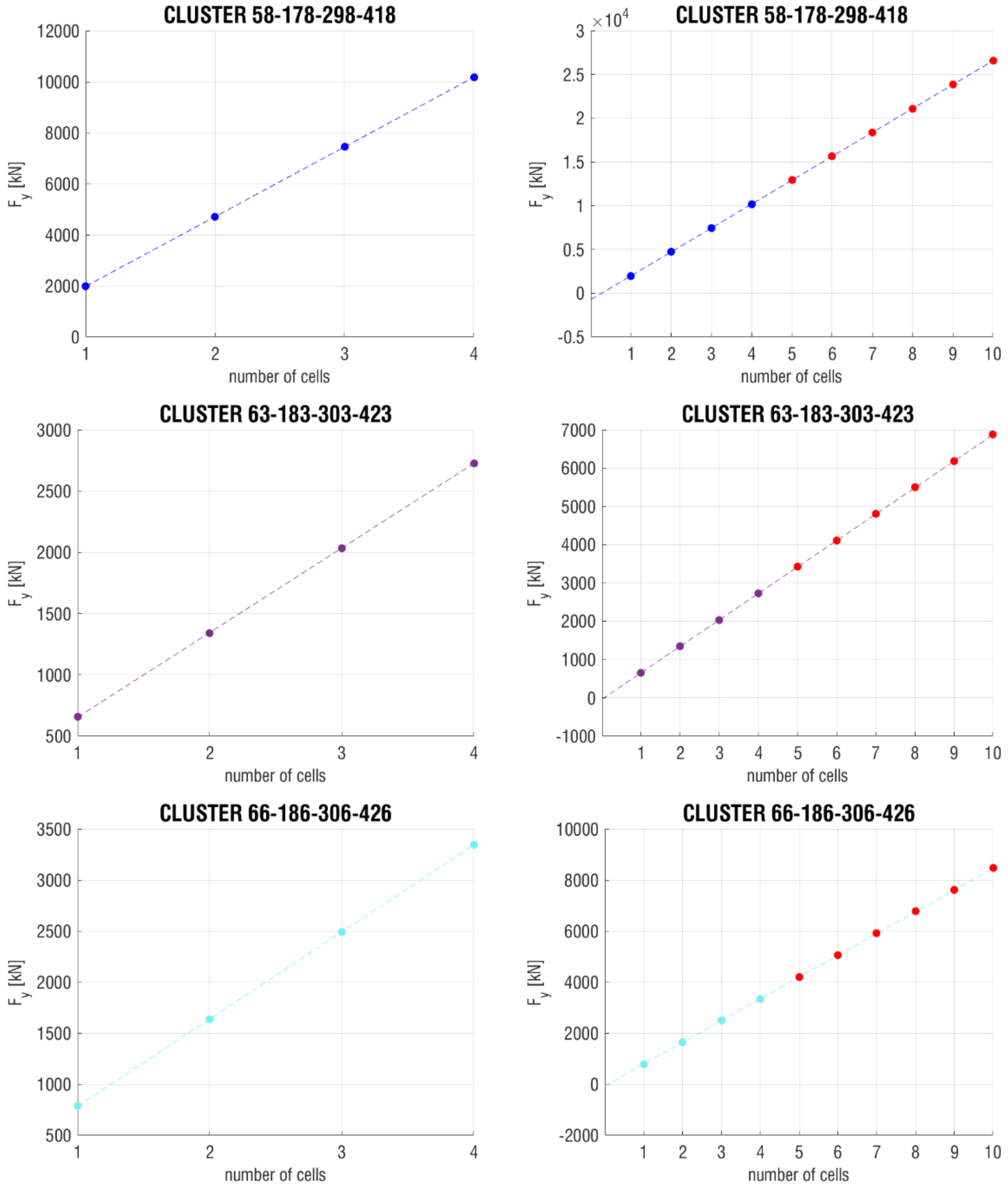


Figure 6.6.17 - linear regression of mean values of F_y of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

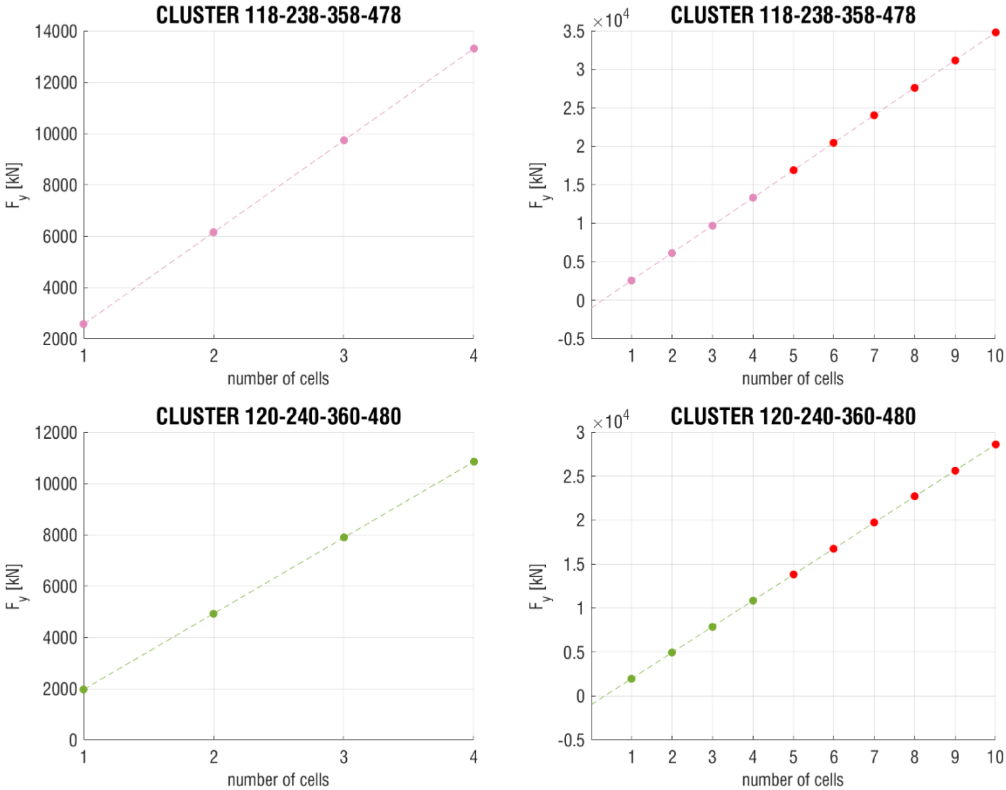


Figure 6.6.17 - linear regression of mean values of F_y of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

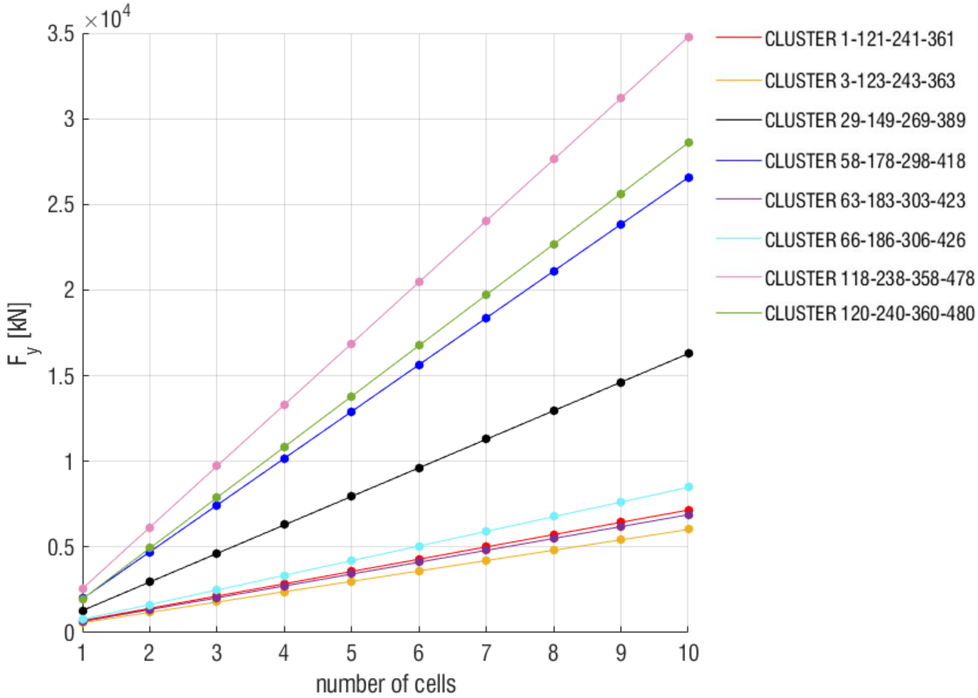


Figure 6.6.18 - F_y regression model of the groups of the clusters analysed

$$F_y(n_{cell}) = p_1 n_{cell} + p_2 \qquad 6.6.3$$

Table 6.6.11 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the F_y polynomial regression model for the analysed clusters

CLUSTER	Coefficients (95% confidence)		Goodness of fit			
	p_1	p_2	SSE	R-square	Adj-R-square	RMSE
1 121 241 361	717,3 (717, 717,6)	-15,11 (-16,96, -13,26)	11,03	1	1	1,74
3 123 243 363	604,8 (604,4, 605,2)	-26,74 (-29,19, -24,28)	19,48	1	1	1,56
29 149 269 389	1666 (1666, 1666)	-374,2 (-374,8, -73,7)	0,9882	1	1	0,351
58 178 298 418	2732 (2732, 2732)	-747,8 (-748,1, -747,5)	0,3184	1	1	0,1995
63 183 303 423	692,6 (692,1, 693,1)	-41,8 (-44,83, -38,76)	29,66	1	1	1,926
66 186 306 426	855,1 (854,6, 855,7)	-72,36 (-75,77, -68,96)	37,36	1	1	2,161
118 238 358 478	3578 (3578, 3578)	-1008 (-1008, -1007)	0.6826	1	1	0.2921
120 240 360 480	2958 (2958, 2958)	-987,1 (-987,8, -986,5)	1,2	1	1	0,3873

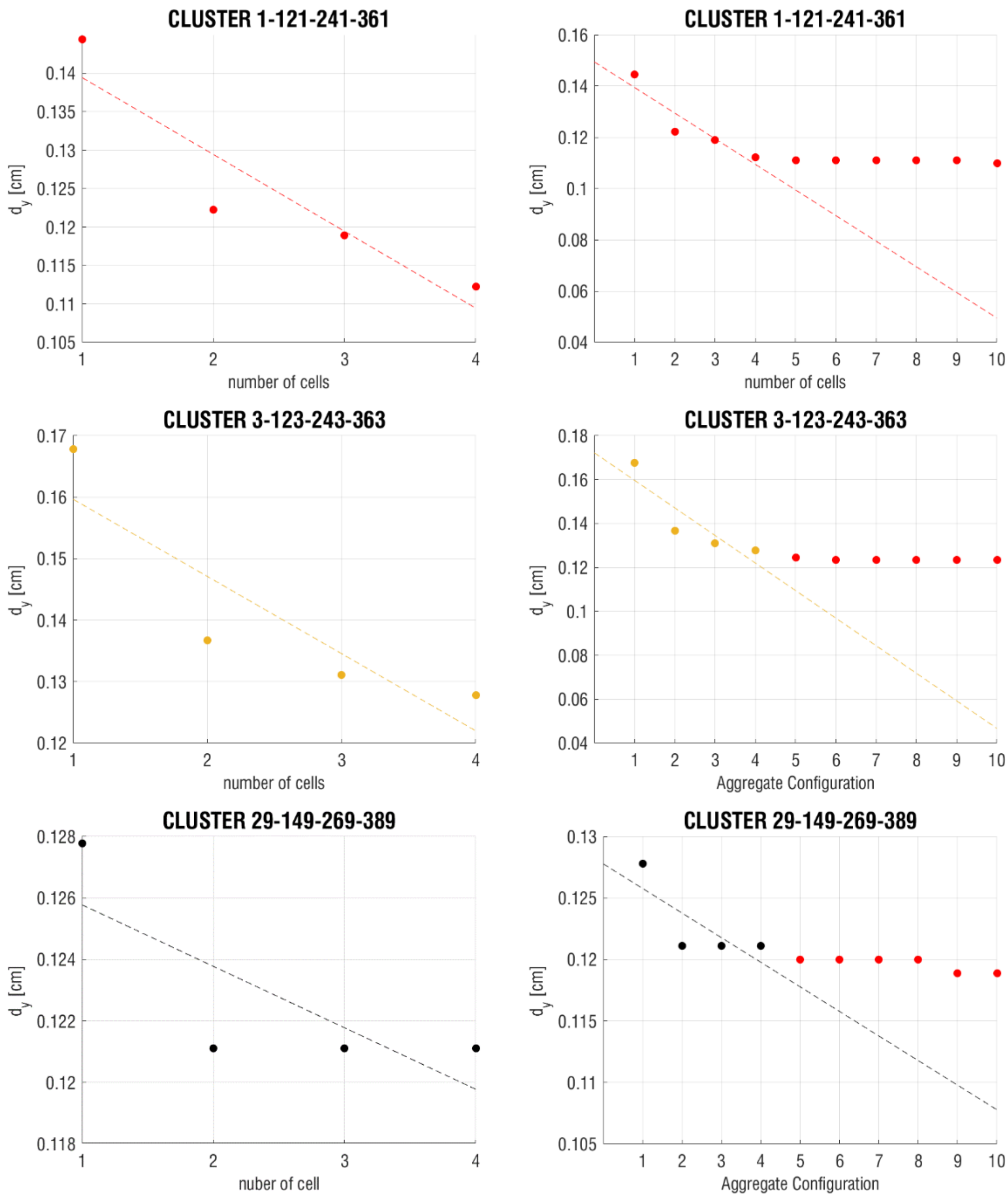


Figure 6.6.19 - linear regression of mean values of d_y of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

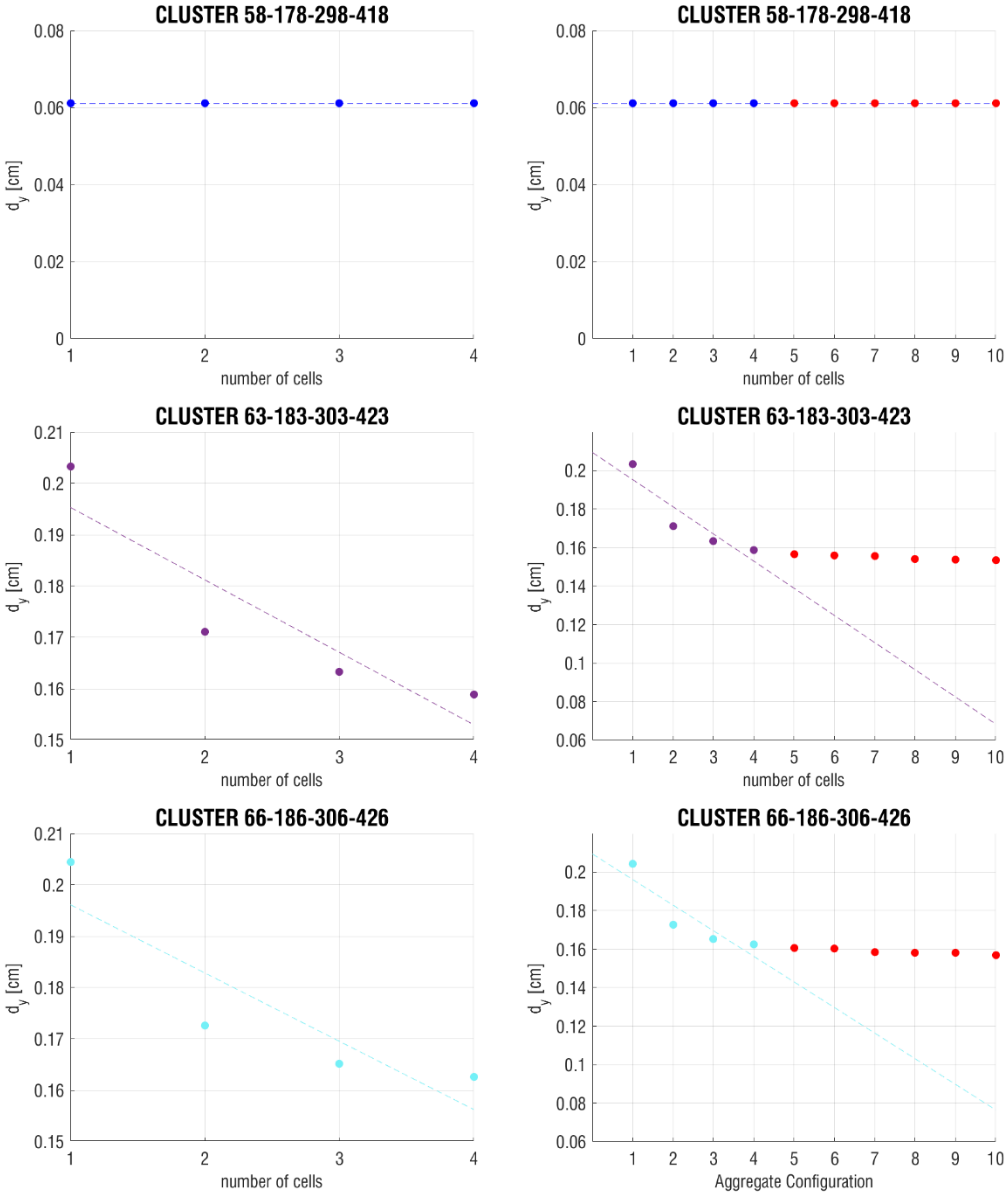


Figure 6.6.19 - linear regression of mean values of d_y of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

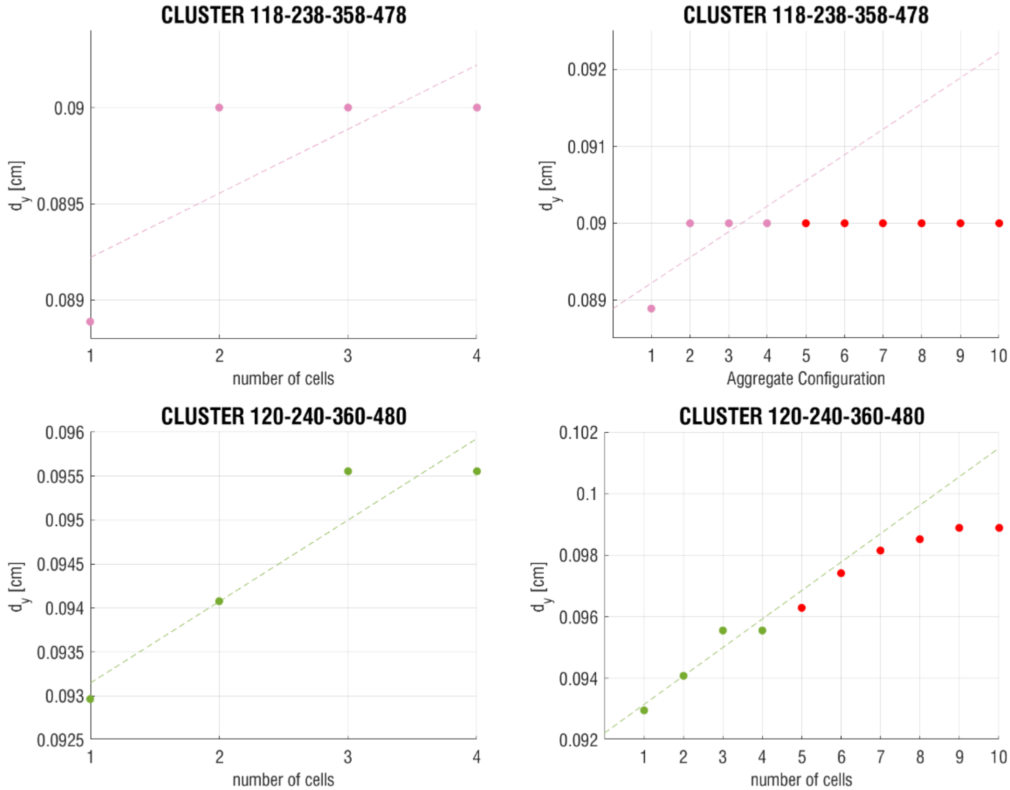


Figure 6.6.19 - linear regression of mean values of d_y of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

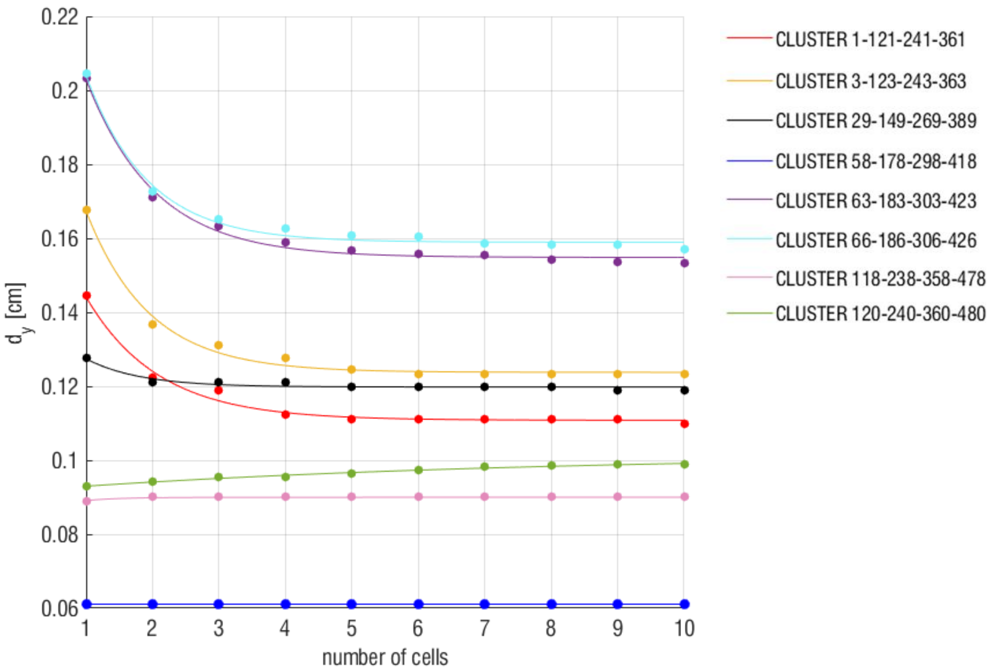


Figure 6.6.20 - d_y regression model of the groups of the clusters analysed

$$d_y(n_{cell}) = ae^{(-bn_{cell})} + c \qquad 6.6.4$$

Table 6.6.12 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the d_y custom regression model for the analysed clusters

CLUSTER	Coefficients (95% confidence)			
1 121 241 361	**a**	**b**		**c**
	0,08367 (0,0623;0,105)	0,9215 (0,6972;1,146)		0,1108 (0,1094;0,1122)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,00001296	0,9874	0,9837	0,001361
3 123 243 363	**Coefficients (95% confidence)**			
	a	**b**		**c**
	0,1255 (0,09455, 0,1565)	1,058 (0,8345, 1,282)		0,1238 (0,1223, 0,1252)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,0000156	0,991	0,9884	0,001493
29 149 269 389	**Coefficients (95% confidence)**			
	a	**b**		**c**
	0,02776 (0,002191;0,05333)	1,278 (0,4099;2,146)		0,1198 (0,1191;0,1206)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,000004379	0,9255	0,9042	0,000791
58 178 298 418	**Coefficients (95% confidence)**			
	a	**b**		**c**
	-	-		-
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	-	-	-	-
63 183 303 423	**Coefficients (95% confidence)**			
	a	**b**		**c**
	0,1251 (0,1008;0,1493)	0,9577 (0,7858;1,129)		0,1548 (0,1534;0,1562)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,00001439	0,9932	0,9912	0,001434

Table 6.6.12 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the d_y custom regression model for the analysed clusters

CLUSTER	**Coefficients (95% confidence)**			
	a	**b**		**c**
66 **186** **306** **426**	0,1324 (0,1001, 0,1647)	1,077 (0,855, 1,299)		0,1589 (0,1575, 0,1604)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,00001571	0,9915	0,9891	0,001498
	Coefficients (95% confidence)			
	a	**b**		**c**
118 **238** **358** **478**	-0,9969 (-3345, 3343)	7,755 (-3347, 3362)		0,08993 (0,08973, 0,09014)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,0000004209	0,6212	0,5129	0,0002452
	Coefficients (95% confidence)			
	a	**b**		**c**
120 **240** **360** **480**	-0,009854 (-0,01257; -0,007143)	0,1411 (0,04125, 0,241)		0,1015 (0,09812, 0,105)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,0000006964	0,9822	0,9771	0,0003154

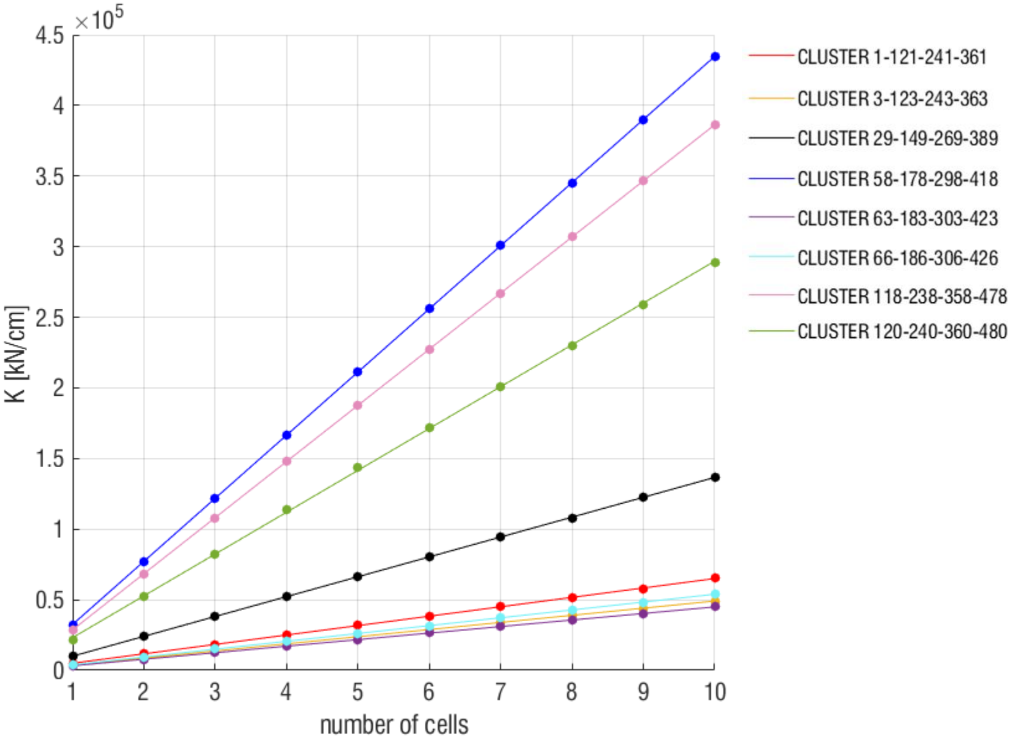


Figure 6.6.21 - regression models for the total stiffness k of the different aggregate configurations of the clusters analysed

$$k(n_{cell}) = p_1 n_{cell} + p_2 \tag{6.6.5}$$

Table 6.6.13 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the k polynomial regression model for the analysed clusters

CLUSTER	Coefficients (95% confidence)		Goodness of fit			
	p_1	p_2	SSE	R-square	Adjusted R-square	RMSE
1 **121** **241** **361**	6663 (6584, 6743)	-1625 (-2117, -1133)	779600	0.9998	0.9998	312.2
3 **123** **243** **363**	5051 (5001, 5102)	-1421 (-1733, -1109)	313500	0,9999	0,9998	198
29 **149** **269** **389**	14070 (13980, 14150)	-4052 (-4597, -3508)	955700	0,9999	0,9999	345,6
58 **178** **298** **418**	44700 (44700, 44700)	-12240 (-12240, -12230)	85,25	1	1	3,264
63 **183** **303** **423**	4631 (4617, 4646)	-1406 (-1494, -1317)	25360	1	1	56,31
66 **186** **306** **426**	5555 (5533, 5577)	-1655 (-1793, -1516)	61430	1	1	87,63
118 **238** **358** **478**	39740 (39710, 39770)	-11050 (-11220, -10890)	86650	1	1	104,1

Table 6.6.13 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the k polynomial regression model for the analysed clusters

CLUSTER	Coefficients (95% confidence)		Goodness of fit			
	p_1	p_2	SSE	R-square	Adjusted R-square	RMSE
120 **240** **360** **480**	39740 (39710, 39770)	-1,050 (-11220, -10890)	86650	1	1	104,1

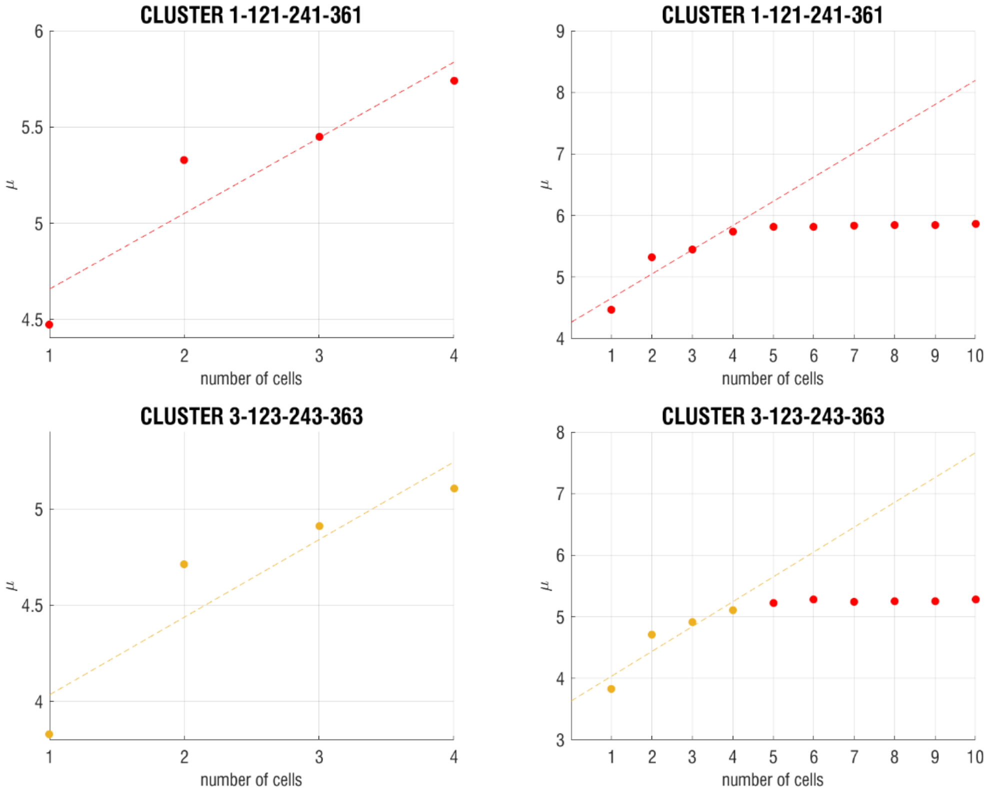


Figure 6.6.22 - linear regression of mean values of μ of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

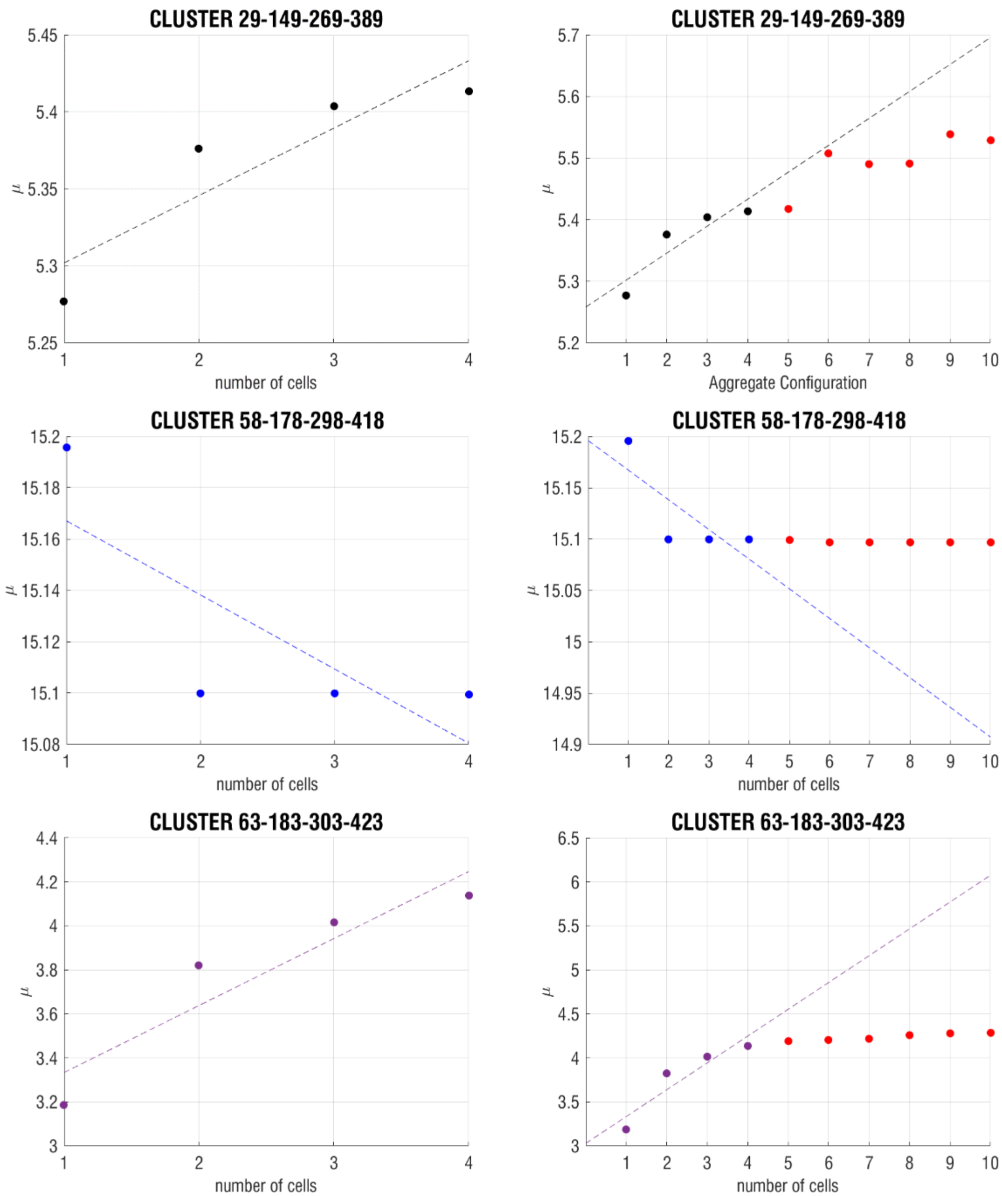


Figure 6.6.22 - linear regression of mean values of μ of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

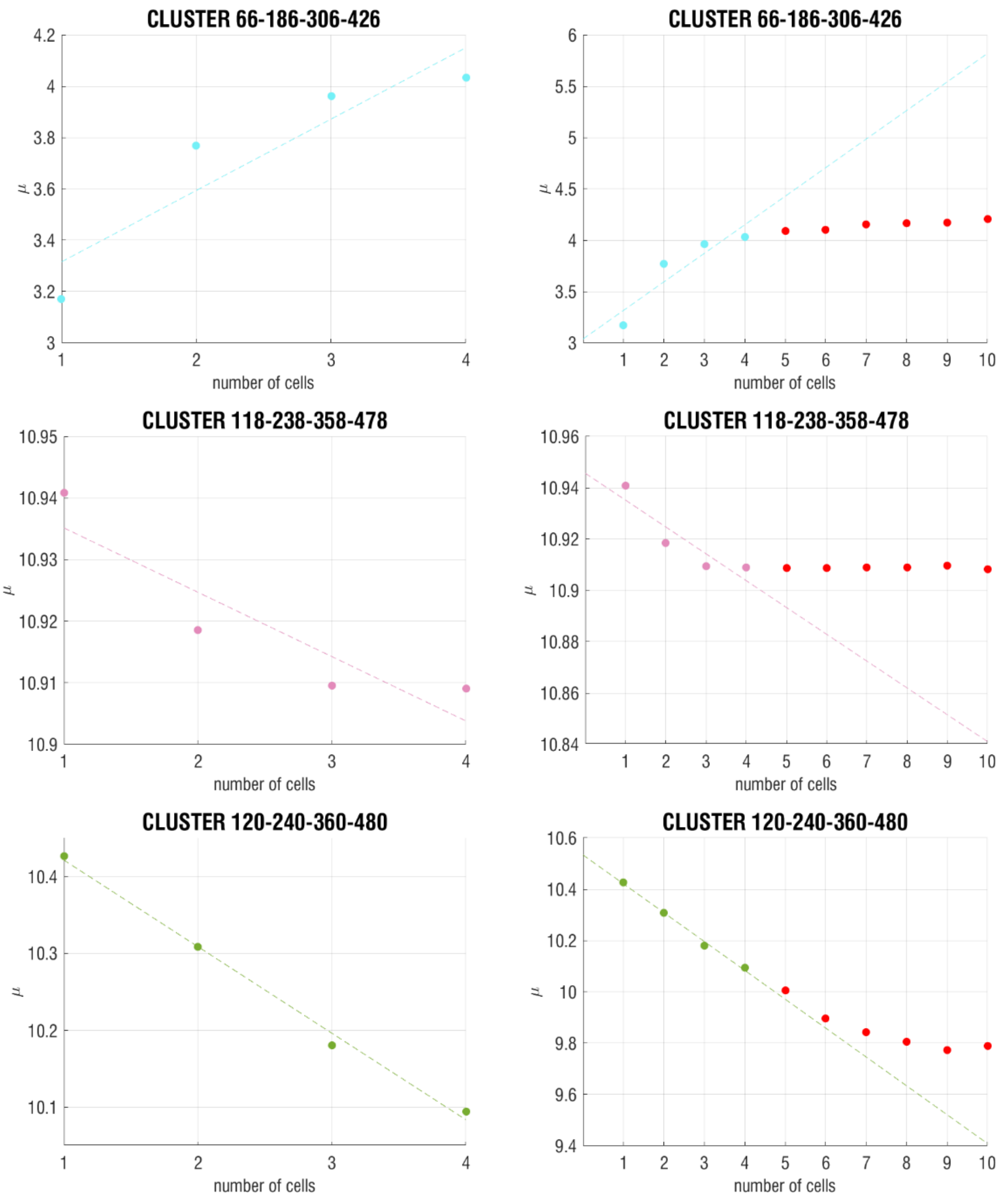


Figure 6.6.22 - linear regression of mean values of μ of the aggregate configurations analysed (1 cell, 2, 3, 4 cells) and verification with further aggregate configurations (5, 6, 7, 8, 9, 10 cells)

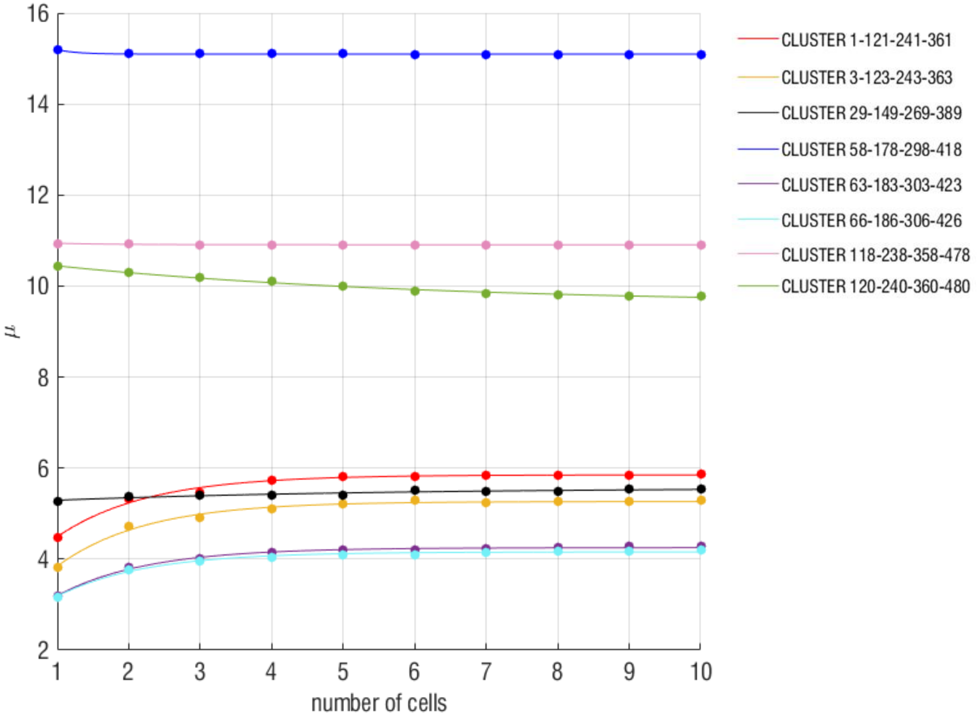


Figure 6.6.23 - μ regression model of the groups of the clusters analysed

$$\mu(n_{cell}) = ae^{(-bn_{cell})} + c \qquad 6.6.6$$

Table 6.6.14 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the μ custom regression model for the analysed clusters

CLUSTER	Coefficients (95% confidence)			
	a	**b**		**c**
1	-3	0,7911		5,851
121	(-3,719, -2,281)	(0,5881, 0,9941)		(5,786, 5,917)
241	**Goodness of fit**			
361	**SSE**	**R-S**	**Adj. R-S**	**RMSE**
	0,02513	0,9855	0,9814	0,05992
	Coefficients (95% confidence)			
	a	**b**		**c**
3	-3,207	0,8144		5,265
123	(-3,797, -2,616)	(0,6574, 0,9714)		(5,215, 5,316)
243	**Goodness of fit**			
363	**SSE**	**R-S**	**Adj, R-S**	**RMSE**
	0,01538	0,9918	0,9895	0,04688
	Coefficients (95% confidence)			
	a	**b**		**c**
29	-0,3414	0,2189		5,568
149	(-0,4316, -0,2512)	(-0,001124, 0,4389)		(5,448, 5,689)
269	**Goodness of fit**			
389	**SSE**	**R-S**	**Adj. R-S**	**RMSE**
	0,004346	0,928	0,9075	0,02492
	Coefficients (95% confidence)			
	a	**b**		**c**
58	-1,004	1,205		16,09
178	(-1,527, -0,48)	(0,719, 1,692)		(16,07, 16,11)
298	**Goodness of fit**			
418	**SSE**	**R-S**	**Adj. R-S**	**RMSE**
	0,004346	0,928	0,9075	0,02492

Table 6.6.14 - Coefficient with 95% confidence bounds and coefficient of goodness of fit of the μ custom regression model for the analysed clusters

CLUSTER	Coefficients (95% confidence)			
63 183 303 423	**Coefficients (95% confidence)**			
	a	**b**		**c**
	-2,34 (-2,719, -1,961)	0,7984 (0,6611, 0,9358)		4,252 (4,218, 4,285)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,002461	0,9705	0,962	0,01875
66 186 306 426	**Coefficients (95% confidence)**			
	a	**b**		**c**
	-2,198 (-2,64, -1,756)	0,8132 (0,6419, 0,9844)		4,158 (4,12, 4,195)
	Goodness of fit			
	SSE	**R-S**	**Adj, R-S**	**RMSE**
	0,008651	0,9902	0,9874	0,03515
118 238 358 478	**Coefficients (95% confidence)**			
	a	**b**		**c**
	0,1171 (0,08926, 0,1449)	1,287 (1,063, 1,511)		10,91 (10,91, 10,91)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,000005	0,9947	0,9931	0,0008458
120 240 360 480	**Coefficients (95% confidence)**			
	a	**b**		**c**
	1,017 (0,9129, 1,121)	0,1939 (0,1227, 0,265)		9,605 (9,46, 9,751)
	Goodness of fit			
	SSE	**R-S**	**Adj. R-S**	**RMSE**
	0,004093	0,9916	0,9892	0,02418

PART III. SEISMIC VULNERABILITY AND ENERGY PERFORMANCE: PROPOSAL OF AN INTEGRATES ASSESSMENT PROCEDURE OF EXISTING BUILDINGS AT URBAN SCALE

7 Integrate procedure of seismic vulnerability and energy performance assessment

7.1 Overview

In the present chapter it is proposed a simplified procedure for the integrated assessment of energy performance and seismic vulnerability of the existing building stock for urban scale applications.

Also in this type of analysis, it is fundamental to prepare a knowledge basis, coherently with the scale of analysis, containing a minimum set of data about the characteristics of buildings which can be processed by means of proper algorithms able to consider the different variables influencing the seismic and the energetic aspects. For this aim, the GMSD database is used as base of information, complemented with data about building environment and plant system.

Then, "indirect" methods are implemented to calculate, at first separately, a seismic vulnerability (IV_S) and an energy performance (IV_E) Index. The two indices are normalized to obtain two consistent values and combined in a synthetic integrated index (IV_I), through a properly coefficients which taking into account the constraints imposed by energy aspects and the invasiveness of seismic retrofit interventions.

7.2 Description of the methodology

The procedure proposed for the integrated assessment of seismic vulnerability and energy performance of existing buildings at the urban scale allows to obtain a final Integrated Index IV_I based on the combination of separately calculated IV_S and IV_E indices. The simplified indirect methods adopted for the assessment of seismic vulnerability and energy performance have been chosen among those available in the literature, depending on the type of data available. The information has been extrapolated from GMSD database complemented with information about building envelope and plant system. The automatic calculation of IV_S, IV_E and IV_I is then performed and, finally, various thematic maps are created.

The methodology is structured according to the three following steps:

2. Construction of GMSD and collection of data about envelope and plant system;

3. Separate automatic implementation in GMSD database of simplified indirect methods for seismic vulnerability and energy performance assessment for each building to calculate respectively IV_S and IV_E for each building;
4. Integration of IV_S and IV_E through the proposed algorithm, resulting in a unique synthetic index IV_I.

7.3 Integration in GMSD of data about building envelope and plant system

The simplified assessment of seismic vulnerability and energy performance at the urban scale has been implemented on the basis of few essential data on the characteristics of buildings, such as geographic location, age of construction, maintenance status, interventions over time, geometrical, typological, constructive and structural characteristics, stored in GMSD database. However, it is necessary to introduce the information fundamentals for the implementation of energy performance assessment. Generally, it is difficult to find these types of data since the large part of existing building stock was constructed in absence of any energetic low, introduced only in the recent years.

For this scope, the information is collected at level single building using as source of information the set of datasheets compiled during the "ANTAEUS" project, in Puglia (Uva *et al.*, 2016), in which a large number of buildings has been screened collecting information about structural materials, constructive elements and details, plan and elevation configuration, type of foundation. These data have been directly implemented for the calculation of IV_S, according the procedure proposed in the framework of ANTAEUS project and have also been extremely useful to extrapolate the typological and technical characteristics of the building envelope and plants, in order to consider also the features concerning the energy performance of buildings.

In case of incomplete information, the missing data can be supplemented by those found through a rapid in-situ or photographic survey; by the analysis of the available technical documentation (Uva, Leggieri, *et al.*, 2019); by using literature references and data from technical standards; or, in some cases, by assuming values that are plausible with the age of construction of the buildings (Uva, Leggieri and Mastrodonato, 2019).

The data obtained has been integrated, processed and managed directly in GMSD database.

7.4 Seismic and energy performance index calculation

The seismic Vulnerability index (IV_S) and the energy performance index (IV_E) have been calculated for each building by implementing separate simplified analysis procedures, using the information collected in the georeferenced databased.

The IV_S index has been calculated through a specifically developed procedure (Uva *et al.*, 2016), in which, depending on the structural type (masonry or reinforced concrete structure), some simple seismic vulnerability parameters that summarize the performance level of the building are calculated, on the basis of morpho-typological, constructive and structural data derived from the forms of "ANTAEUS" project. The input data are the following:

- period of construction and interventions over time;
- geometrical and morphological characteristics of the structural unit;
- general morphology of the site;
- maintenance level;
- damage of non-structural elements;
- exposure (importance of the building).

A class of vulnerability (A, B, C, D, from the best to the worst class) is assigned to each vulnerability parameter according to proper rule matrices, and a corresponding numerical score p_i is calculated. The overall IV_S is defining by using Eq. 7.4.1, normalizing the weighted sum of the scores between 0 and 1 (to minimum and maximus seismic vulnerability value, respectively).

$$IV_S = \sum_{1=1}^{11} \frac{w_i p_i}{w_i p_{i,max}} = \frac{\sum w_i p_i}{326{,}25} \qquad 7.4.1$$

where p_i and w_i are, respectively, the i-th score and weight assigned to each parameter and $p_{i,max}$ is the score corresponding to the lowest vulnerability class, D (Table 7.4.1).

Table 7.4.1 - Vulnerability parameters, scores p_i and weights w_i for masonry buildings

Parameters	Score p_i				Weight w_i
	A	B	C	D	
1. Type and organization of the resisting system	0	5	20	45	1.50
2. Quality of the resisting system	0	5	25	45	0.25
3. Conventional capacity	0	5	25	45	0.50
4. Topographic conditions	0	5	25	45	0.50
5. Floors	0	5	15	45	0.75
6. Configuration in-plan	0	5	25	45	0.50
7. Configuration in elevation	0	5	25	45	1.00
9. Roof	0	5	15	45	1.00
10. Non-structural elements	0	5	25	45	0.25
11. Maintenance level	0	5	25	45	1.00

As far as the evaluation of energy performance is concerned, there is an objective difficulty in finding reliable information both on consumption data (for privacy issues) and on the thermo-physical characteristics of the building envelope and equipments (which only in very recent times are subject to dedicated standards and design). With reference to these aspects, it is therefore necessary to compensate for the lack of information by using data derived from other available documentation, rapid surveys, standards and reference literature, experience. Following this approach, "feasible" assumptions have been made for the main characteristics and numerical values age of construction; typological characteristics of buildings belonging to homogeneous classes; type of energy carrier available; energy costs at the time of construction; context in which the building is located (Uva, Leggieri, *et al.*, 2019). In the present work, the objective is to define a synthetic index IV_E able to give a first rapid screening about the energy performance of building stock, using a suitable procedure easily implementable using the available geo-referenced dataset.

As a first step, the annual heating requirement ($Q_{H,nd,i}$) is calculated for each building, adapting the procedure of (Ascione *et al.*, 2013), which is classified as a "direct" method, as previously defined.

The required data are the climatic characteristics of the site, the geometrical and thermo-physical features of building elements and sub-components, and have been extrapolated or derived from different sources, and integrated into the GIS.
($Q_{H,nd,i}$) is calculated by using eq. 7.4.2:

$$Q_{H,nd,i} = Q_{H,TR,i} + Q_{H,VE,i} - \eta_{H,gn}(Q_{SOL,i} + Q_{END,i}) \; [MJ] \qquad 7.4.2$$

Where $Q_{H,TR,i}$ and $Q_{H,VE,i}$ are the heat losses due, respectively, to the transmission through the building envelope and to the ventilation; $\eta_{H,gn}$ is an utilization factor; $Q_{SOL,i}$ and $Q_{END,i}$ are, respectively, the solar and the endogenous gains (Ascione *et al.*, 2013).
To have an IV_E directly comparable with IV_S, the result should be normalised between 0 and 1. The procedure proposed by the authors to define IV_E involves the calculation of the annual heating demand for the as-built condition ($Q_{H,nd,ab}$), and for "Reference Building" ($Q_{H,nd,rb}$), which is defined as a building identical to the real one in terms of geometry, geographical orientation and climatic conditions, but with building envelope and plant system characterized by minimum performance standards ('DI 192-2015', 2015).

$$IV_E = 1 - \frac{Q_{H,nb,rb}}{Q_{H,nb,ab}} \qquad 7.4.3$$

The final result is comprised in the range [0, 1]. 0 corresponds to a high energy performance level and therefore to a minimum "energy vulnerability" (the value 0 is assumed in case of $IV_E < 0$), while. 1 corresponds to a low energy performance level and to a maximum "energy vulnerability".

7.5 Integrated assessment algorithm

IV_S and IV_E are separately calculated for each building in order to derive two coherent values that are directly comparable. The last step is to provide an algorithm able to combine these two indices into a unique synthetic indicator able to highlight the critical situations within the investigated sample of buildings.
The interaction of the two fundamental aspects of seismic vulnerability and energy performance in existing buildings involves several variables and different viewpoints, e.g. social, functional, economic and environmental aspects (Pons and Aguado, 2012),

which could be taken into account among different criteria and attributes (Mosalam *et al.*, 2014). The choice of the suitable factors to be considered is strictly linked to the type and the purpose of the analysis.

If the aim of the evaluation is to have a preliminary analysis of the current state of the existing building stock, the prevailing aspects are:

- maintenance level and degradation, generally connected to the construction period;
- exposure to hazardous agents and user profile, related to the importance of the building;
- difficulty level of the retrofit interventions.

The main objective of the integrated approach proposed is to point out possible performance criticalities at a large scale, in a rapid way and using few information, in order to have a first screening of the existing buildings stock and obtain priority lists for more detailed analyses and interventions. For this reason, we have chosen as a primary criterion for the combination of the indices the level of difficulty and invasiveness of the interventions required for the simultaneous reduction of seismic vulnerability and improvement of energy performance.

Generally, structural interventions for the reduction of seismic vulnerability are characterized by greater constrains and execution difficulties than energy retrofit interventions to reduce consumption and improve energy performance. Consequently, an "intervention capacity coefficient" $i_{c,is}$ has been introduced, defined as follows:

for IV_S, $i_{c,S} = 0.6$;

for IV_E, $i_{c,E} = 0.4$.

Finally, the "integrated Evaluation Index" I_I is determined by means of the following equation:

$$I_I = \sqrt{i_{i,S}(IV_S)^2 + i_{i,E}(IV_E)^2} \qquad 7.5.1$$

For each building, a value of I_I is calculated using the geo-referenced dataset in the GIS environment. In this way, it is possible to display different maps of the current state of the existing building stock and elaborate different kinds of scenarios.

7.6 Application to the case study of Foggia

The proposed integrated assessment procedure has been applied to the municipality of Foggia, a city of about 150.000 people located in the north of Puglia.

As far as the seismic characterization of the site is concerned,, according to the first seismic classification of the city, dated back to 1981, Foggia belongs to the seismic zone 2, defined as zone in which strong earthquakes can occur (Ministero dei lavori pubblici, 1981). According to the current Italian code, Foggia is characterized by a peak ground acceleration (a_g) 0.135 g, with exceeding probability (P_{V_R}) of 10% in a reference period (V_R) of 50 years (Ministero delle Infrastrutture e dei Trasporti, 2018).

According to the climate classification introduced by Italian Law in 1993, Foggia belongs to zone D, with 1530 degree-days (*DPR n. 412*, no date).

A preliminary analyses of the urban fabric based on ISTAT dataset (ISTAT, 2011), shows that more than half of the building stock of the entire municipality of Foggia was built between 1919 and 1970, and that the construction age about 75% of the buildings is prior to 1980, before any seismic and energy standards were issued.

The sample under investigation is located in Borgo Croci, an ancient district in the historical centre of Foggia (Figure 7.6.1) consists of 148 buildings (Figure 7.6.2). In Borgo Croci, the percentages of buildings in unreinforced masonry and reinforced concrete are in line with those of the entire municipality (Figure 7.6.3), with a prevalence of building aggregates with a masonry structure (91%), most of which (30%) was built before 1919.

Figure 7.6.1 - The district of Borgo Croci in the Municipality of Foggia; b) the sample of buildings analysed

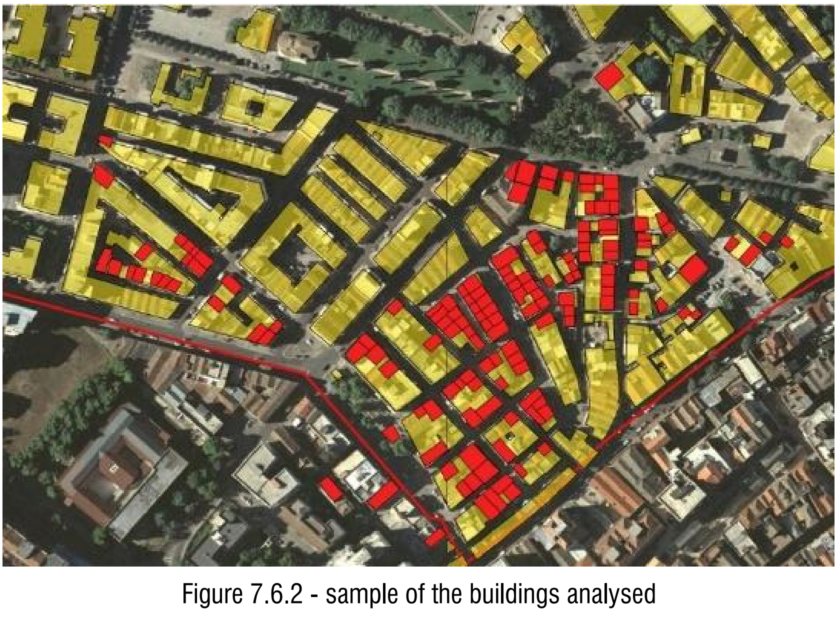


Figure 7.6.2 - sample of the buildings analysed

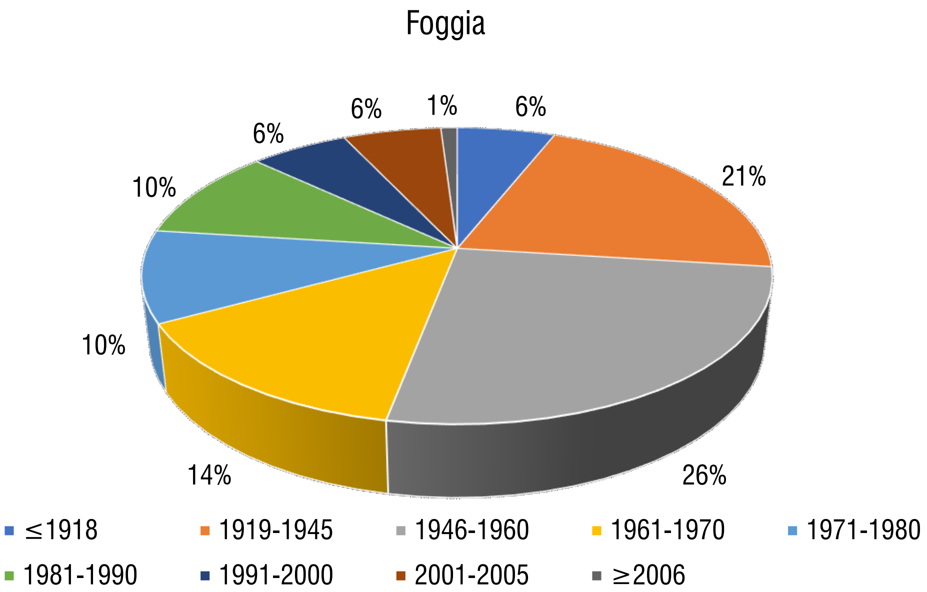


Figure 7.6.3a - Percentages of buildings per age of construction of Foggia

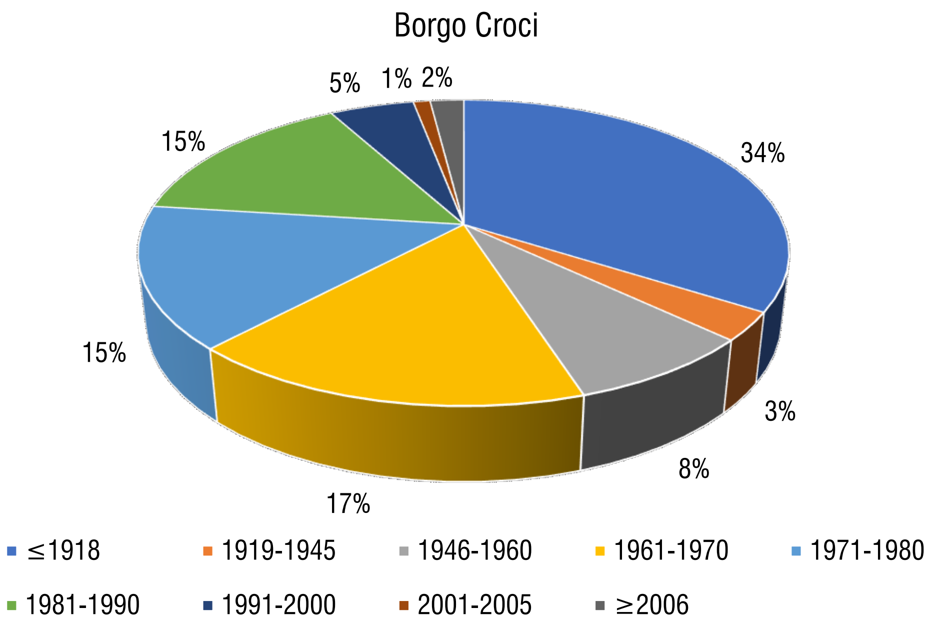


Figure 7.6.3b- Percentages of buildings per age of construction of Borgo Croci

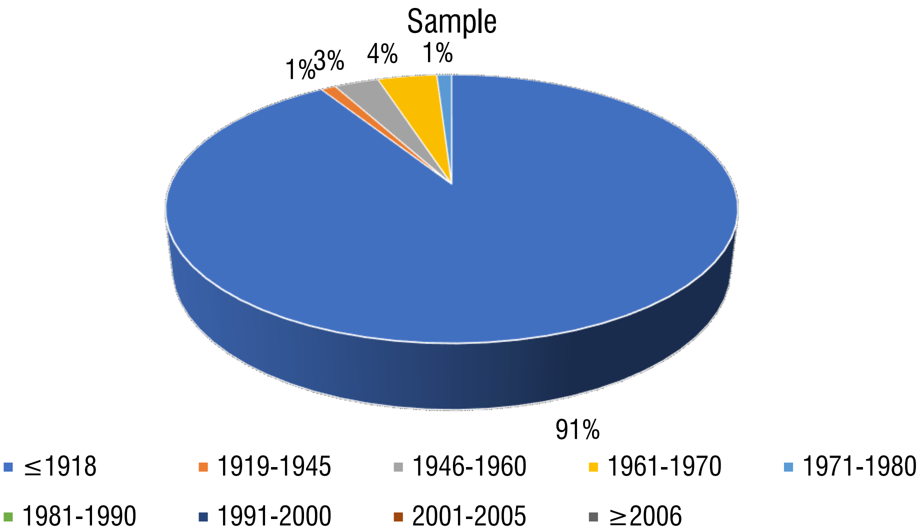


Figure 7.6.3c - Percentages of buildings per age of construction of the sample analysed

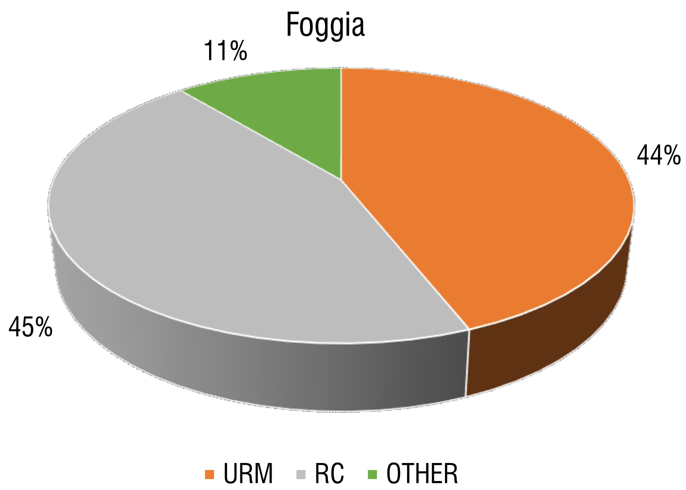


Figure 7.6.3d - Percentages of buildings per structural typology of Foggia

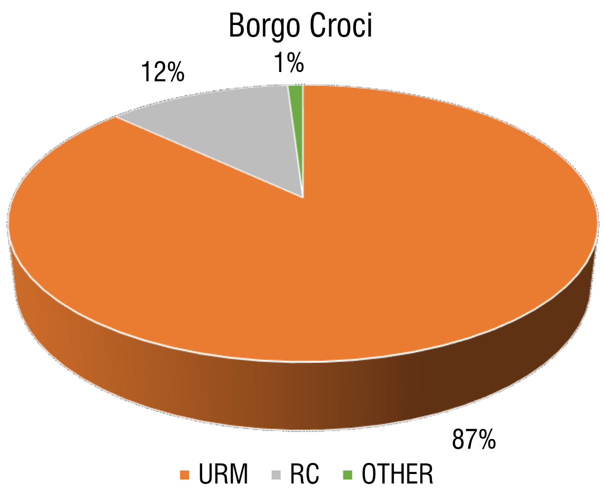


Figure 7.6.3e - Percentages of buildings per structural typology of Borgo Croci

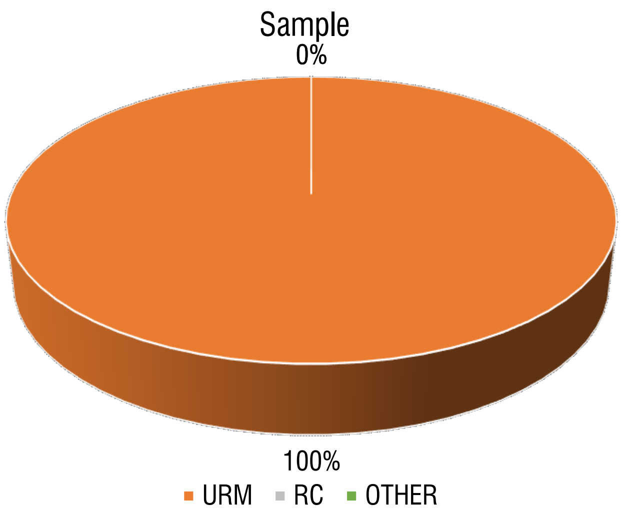


Figure 7.6.3f - Percentages of buildings per structural typology of the sample analysed

7.6.1 Data gathering and GIS implementation

The implementation of the procedure was carried out on the basis of a GIS georeferenced database built by implementing different kind of datasets ISTAT data are an important source that can be directly implemented into GIS, useful for a first analysis of the entire municipal territory, through which it was possible to elaborate, the distributions of the buildings with regard to the age of construction, the structural typology, the number of floor and the state of conservation.

Orthophotos and Technical Regional Maps allow to have a realistic visualization of the urban fabric and provide data regarding the aggregation of buildings and urban blocks. In particular, it is possible to have information about the morphology and typology of construction (civil building, tumbledown building, building under construction, underground structure) and information about height of building.

The overlap of the information derived by these different sources has allowed u to analyze the entire municipal territory in view of the compilation of the CARTIS forms, for identifying the homogeneous sectors, the related structural typological building classes and the recurrent features for each of them. Then, in the GIS system, the information collected for a typological class has been associated to each building that is recognized as belonging to it. In the specific geographic context of application of the research work, public georeferenced datasets about the individual buildings were not available, but it was possible to exploit the "ANTAEUS" database (Uva *et al.*, 2016), implementing in the GIS environment the information of the forms by the geocoding of the addresses. In this way, for each building of the sample investigated, it has been possible to retrieve all the information required to calculate in an automatic way IV_S, IV_E and finally IV_I.

7.6.2 Integrated assessment procedure

By using the above-mentioned procedure and based on the georeferenced dataset, the IV_S and IV_E indices have been evaluated for each building.

The assessment of the seismic vulnerability index has been performed using the data collected in the ANTAEUS forms and applying the algorithm for URM buildings.

The IV_E index has been calculated using the procedure illustrated in Section 2.2, adopting the following input data: design internal temperature equal to 20 °C; heating period ranging from 1st November to 15 April, for 12 hours daily as required by the codes (DPR n. 412); average external temperature on a monthly basis as provided by UNI 10349 (Uni, 2016). The information about the thermo-physical characteristics of the building envelope has been derived from rapid surveys, from data available in the compiled forms or by assuming values of heat transmittance available in the literature or in technical standards, depending on the typology of the elements and the age of construction reported (Table 7.6.1).

Table 7.6.1 - Transmittance value for components of the building envelope

	U (W/m²K)					
Typology	**Pre 1920**	**1920 1945**	**1946 1971**	**1972 1991**	**1992 2005**	**Post 2005**
Opaque Vertical Facades						
Square stones	2,99	2,99	2,99	2,99	2,99	2,99
Tuff blocks	1,41	1,41	1,41	1,41	1,41	2,99
Solid bricks	1,48	1,48	1,48	1,48	1,48	1,48
Hollow bricks	0,00	1,76	1,76	0,8	0,61	0,34
Concrete blocks	0,00	0,00	2,80	0,79	0,60	0,34
Opaque Horizontal Roofs						
Wooden	1,80	1,80	1,80	1,80	1,80	1,80
Brick and concrete	0,00	2,20	2,20	1,41	0,74	0,3
Steel	2,48	2,48	2,48	2,48	2,48	2,48
Masonry vaults	0,00	2,07	2,07	2,07	2,07	2,07
Lower floor						
Wooden	2,04	2,04	2,04	2,04	2,04	2,04
Brick and concrete	0,00	1,30	1,30	1,24	0,77	0,33
Brick and steel	0,00	1,87	1,87	1,87	1,87	1,87
Masonry vaults	1,58	1,58	1,58	1,58	1,58	1,58
Windows						
Wooden frame single glazed	4,60	4,60	4,60	4,60	4,60	4,60
Aluminium frame single glazed	6,10	6,10	6,10	6,10	6,10	6,10
Aluminium frame double glazed	3,20	3,20	3,20	3,20	3,20	3,20
PVC frame double glazed	0,00	0,00	0,00	0,00	1,40	1,40

The orientation of the buildings has been estimated through GIS visualization and corrected by using the exposition coefficients. The presence of thermal bridges has been considered using a correction factor that increases the thermal transmission losses, and is assumed equal to 10% for masonry buildings (Ascione *et al.*, 2012).
The position within the aggregate was useful to identify the external vertical surfaces and the surfaces bordering the other building units, where the heat losses for transmission are negligible.
The same procedure and data have been used for the calculation of the heat loss of the Reference Building, in which the building envelope is assumed to have the minimum heat transmittance requirements provided by Italian standards (Dl 192, 2015).
The values obtained for each building have been then normalized to obtain an IV_E comprised between 0 and 1.
The algorithms for the calculation of IVS and IVE have been implemented within the GIS environment, as well as the one for the integrated assessment that calculates the index II combining the IV_S and IV_E by Eq. 7.5.1. All the procedure of assessment, therefore, is automatically performed in the GIs by using the georeferenced dataset, providing different visualization maps of the results.
Figure 3 reports a synthesis of the application performed on the case study, in terms of the average values obtained for the 3 indices. In particular, the diagrams on the left show the distribution of the buildings per average value of the index and per construction age. The diagrams on the right report the distribution of the buildings into the Vulnerability Classes obtained by dividing the range of definition of the indices [0-1] into 4 sub-intervals (L-Low; ML-Medium-Low; M-Medium; H-High) corresponding to increasing vulnerability levels (Table 7.6.2).

Table 7.6.2 - class of seismic and Energy Vulnerability and level of criticality

Range	**Seismic vulnerability**	**Energy vulnerability**	**Integrate classification**
0,00-0,25	Low (L)	Low (L)	Not Critical (NC)
0,25-0,50	Medium-Low (ML)	Medium-Low (ML)	Moderately Critical (MC)
0,50-0,75	Medium (M)	Medium (M)	Critical (C)
0,75-1,00	High (H)	High (H)	Very Critical (VC)

With regards to the IV_S, the results show that the buildings with a construction age prior than 1920 have a higher seismic vulnerability (Figure 7.6.4a). Considering the entire sample, about 73% is characterized by Medium or Low vulnerability (Figure 7.6.4c). The highest value of the energy vulnerability corresponds instead to buildings realized between 1946 and 1971, where the majority of the sample belongs (Figure 7.6.4a) Therefore, it can be observed that the most part of building investigated has a bad energy performance.

With regard to the integrated index IV_I, which considers the constraints and difficulties in retrofit interventions, the highest level of criticality is reached by buildings realized between 1920 and 1945 (Figure 7.6.4b). Overall, bout 75% of the sample is characterized by a critical level according to the integrated classification (Figure 7.6.4d).

An effective overview of the current state of the buildings investigated is provided by GIS thematic maps (Figure 7.6.5b - GIS thematic visualization IV_E distribution), which visualize the vulnerability results associated to each building, identified with is cadastral perimeter, in an aerial view.

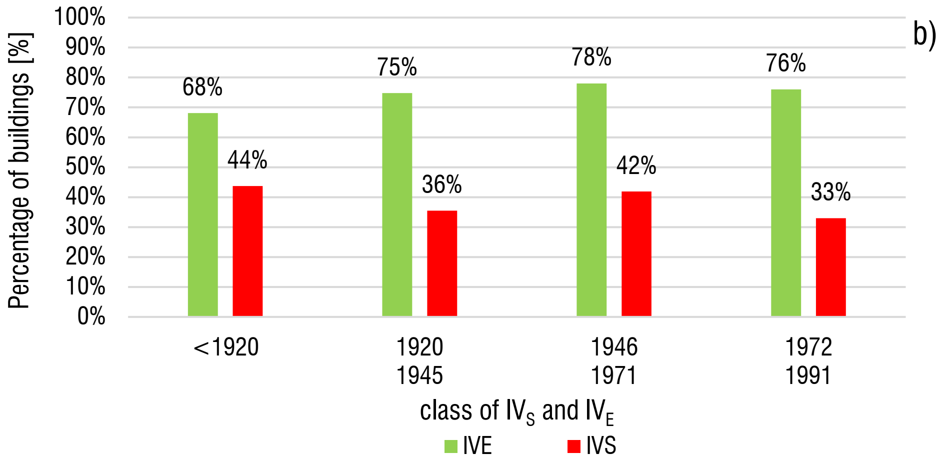


Figure 7.6.4a - Average value of IVS and IVE per age of construction

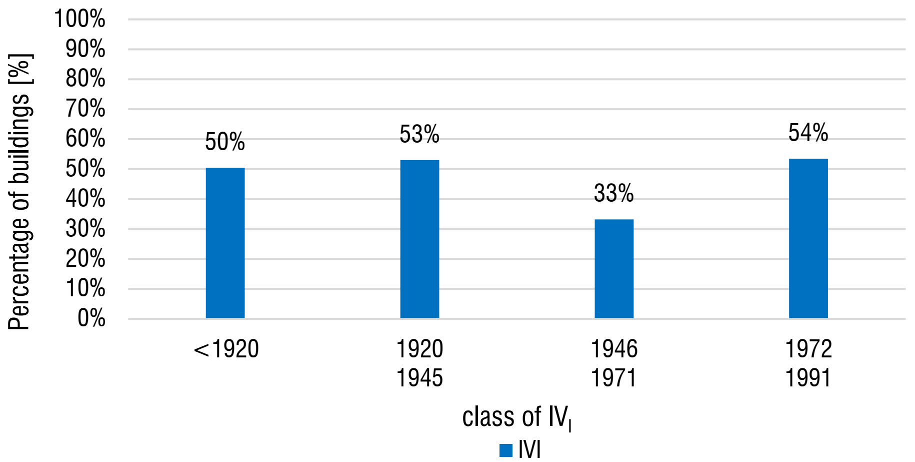


Figure 7.6.4b - Average value of IVI per age construction

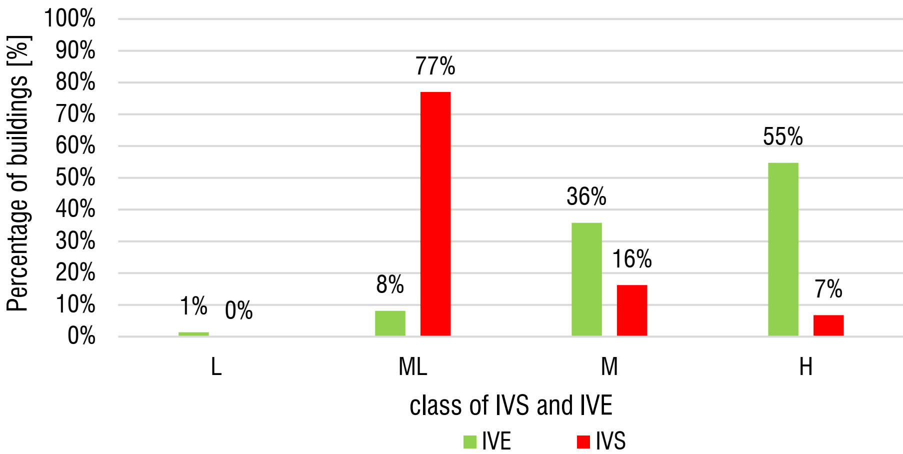


Figure 7.6.4c - Distribution of IVS and IVE per vulnerability classes

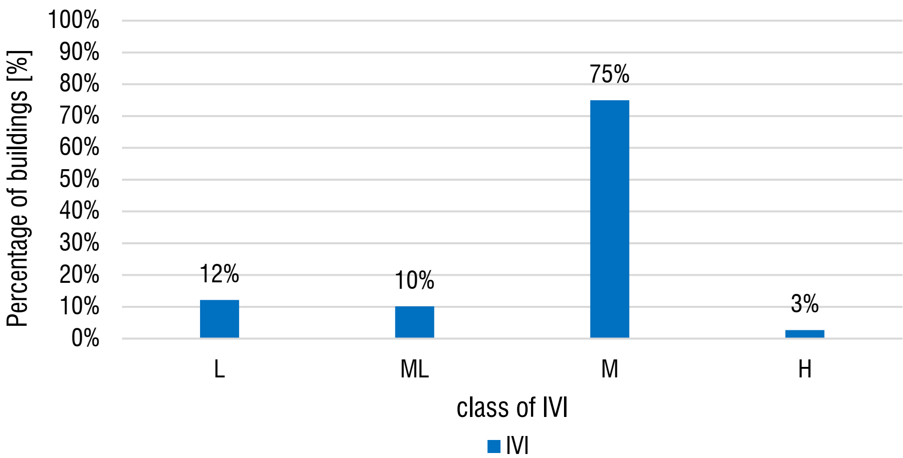


Figure 7.6.4d - Distribution of IVI per vulnerability classes

Figure 7.6.5a - GIS thematic visualization IV_S distribution

Figure 7.6.5b - GIS thematic visualization IV_E distribution

Figure 7.6.5c - GIS thematic visualization IV_I distribution

CONCLUSION AND FUTURE DEVELOPMENTS

The procedure proposed in the present work allows the extraction, integrate and elaborate data from different sources to construct a geo-referenced cartographic and descriptive database in a GIS environment which is the fundamental reference basis for any assessment procedures of the existing residential building stock at a large scale.
The application has demonstrated that it is possible to easily manage different typology of data and obtain a homogeneous information on the urban territory, filling in the possible lacks at the different scales.
On the basis of such a structured georeferenced database, an indirect method for the seismic vulnerability assessment has been implemented in a simple and rapid way, deriving the results for a large number of buildings but it can be possible also to implement other several types of assessment at large scale with regard to different aspects of the existing building stock.
Indeed, by using the same data, it has been possible elaborate a simplified typological-mechanical procedure developed for the analyses at urban scale of the masonry building aggregates. In this case the data is useful for a statistical sampling of the structural-typological building classes and relative typical aggregate configurations implementing in automatic way numerical modelling and analyses. Despite the complicity of the topic regarding the analyses of the structural behaviour of masonry aggregates, the strong simplification in the numerical approach allows a analyses suitable for the large scale and for the aim of the methodology, indeed, by means of the relations defined for same group of clusters, it is possible to predict characteristic parameters which define the seismic behaviour of the masonry aggregates on the bases of the knowledge of few parameters of the single component structural unit.
It should recalled that, analysing the results of the procedure, the statistical sampling of the classes of buildings on the bases of recurrent geometrical typological and structural characteristics, involves the grouping of numerical models with a different structural and seismic behaviour and thus, it is required a further clusterization within the same building class. However, this operation turns out to be easily implementable due to the low computational effort required by the procedure.

The future developments will provide the extension of the analyses to other aggregate configurations composed by structural units with different characteristics. Furthermore, accounting for more information and more variables such us the variability of seismic action, it will be elaborated full vulnerability curves for the different typical masonry aggregates.

The gathering and integration of data from different sources represent a fundamental step also for the implementation of the integrated approach to seismic vulnerability and energy performance assessment, to enrich the knowledge about the buildings stock and retrieve the input information for the algorithms, however, many difficulties typically arise about the availability and quality of the data especially about building envelope and plant system. This because only in the last few years, the attention to the issue of energy performance are growing, indeed, the application of the relative regulatory requirement regard only the buildings of recent construction, while, for the most of existing building stock it is no possible to find data about energy behavior. The issue of incomplete knowledge has been overtaken deriving the missing data from the available public sources or introducing plausible assumptions, which can be subsequently verified and calibrated through the comparison with detailed analyses on individual buildings.

Moreover, the application of procedures at the regional scale for the energy performance assessment of buildings is quite a recent topic in scientific research if compared to the field of seismic vulnerability, for which a well-established framework is available since many decades and, therefore, it is possible to rely on a large statistical database and acknowledged algorithms. With regard to the procedures for evaluating the energy efficiency, instead, there are very few tools and reference data which can support the appropriate choices for large-scale applications as a consequence, the reliability and accuracy of the results is different.

It is worth to highlighting that, in the algorithm proposed, the criterion of combination between the seismic vulnerability and the energy performance is based only on one aspect, which is related to the constrains and difficulty of retrofit interventions. Further development should concern the analysis of other variables which have an influence

on both performance levels, such as maintenance level, degradation, exposure to hazardous agents, user profile and cost of retrofit interventions.
An important issue remains, of course, the availability of information and the associated uncertainty, which are often connected to the specific context of analysis. Moreover, the verification procedure performed on a sample of actual buildings highlights the necessity to verify and correct the information collected at a large scale to define the building typological classes through a comparison with the characteristics of a number of individual buildings, for which the gathering data could be burdensome. However, a further consideration should be made about the verification of “robustness” of the procedure of data extraction and integration from different sources, indeed, it shall be such as to introduce not significant errors with respect to the resolution of indirect seismic vulnerability assessment procedures. With regard to this aspect, a further development could be the realization of an automated procedure able to check and correct the data through a comparison between information at different scale and to obtain a data with less uncertainty and higher reliability.
The use of GIS environment allows to create a tool connected to a relational database easily implementable and searchable that can support the management of urban areas. Such a tool is particularly useful as a support for decision makers, who can so have a global picture of the risk on a wide territory and use it as a rational basis for programming rehabilitation strategies and risk mitigation measures.
Finally, the proposed approach is, in perspective, an important tool for public authorities and private owners or managers, because allows to elaborate a preliminary rapid screening of the current state of the building stock at a large scale, providing a priority list for further detailed analyses and for programming development plans and investments. The application to the cases study has demonstrated the effectiveness of the procedures in the data mining, integration and processing, and the potentiality to provide a powerful knowledge framework about the building stock and its vulnerability. As a further step, it is necessary in the future to perform extensive applications on larger samples and perform detailed analyses at the scale of individual buildings, in order to validate and calibrated the procedure.

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REFERENCES

Abrams, D. P. (1992) 'Strength and behavior of unreinforced masonry elements', *10th World Conference on Earthquake Engineering, Madrid, Spain*, pp. 3475–3480.

Aksoezen, M. *et al.* (2015) 'Building age as an indicator for energy consumption', *Energy and Buildings*, 87, pp. 74–86. doi: 10.1016/j.enbuild.2014.10.074.

Albuquerque, P. (2008) 'Seismic vulnerability assessment of medium-rise buildings using the Index Method : the case of block # 22 of Santa Maria Hospital', pp. 1–19.

Allen, D. and Rainer, J. (1995) 'Guidelines for the seismic evaluation of existing buildings', *Can J Civ Eng*, 22, pp. 500–505.

Amaro-Mellado, J. L. and Bui, D. T. (2020) 'Gis-based mapping of seismic parameters for the pyrenees', *ISPRS International Journal of Geo-Information*, 9(7). doi: 10.3390/ijgi9070452.

Ascione, F. *et al.* (2012) 'Different methods for the modelling of thermal bridges into energy simulation programs: Comparisons of accuracy for flat heterogeneous roofs in Italian climates', *Applied Energy*, 97, pp. 405–418. doi: 10.1016/j.apenergy.2012.01.022.

Ascione, F. *et al.* (2013) 'Analysis and diagnosis of the energy performance of buildings and districts: Methodology, validation and development of Urban Energy Maps', *Cities*, 35, pp. 270–283. doi: 10.1016/j.cities.2013.04.012.

ASHRAE 90.1 (2016) 'Energy Standard for Buildings Except Low-Rise Residential Buildings', *ASHRAE/IESNA Standard*, 2016, pp. 404–636.

ATC (1985) 'Earthquake damage evaluation data for California', *Atc-13*, p. 492. Available at: http://nisee.berkeley.edu/elibrary/Text/S22323.

ATC (1988) 'Rapid Visual Screening of Buildings for Potential Seismic Hazards'.

Baggio, C. *et al.* (2007) 'Field Manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES)', *JRC Scientific and Thechnical Reports*, pp. 1–100.

Bahu, J.-M. *et al.* (2015) 'Towards a 3D Spatial Urban Energy Modelling Approach', *International Journal of 3-D Information Modeling*, 3(3), pp. 1–16. doi: 10.4018/ij3dim.2014070101.

Bal, I., Gulay, F. and Tezcan, S. (2008) 'A New Approach for the Preliminary Seismic Assessment of RC Buildings: P25 Scoring Method', in.

Ballarini, I., Corgnati, S. P. and Corrado, V. (2014) 'Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project', *Energy Policy*, 68, pp. 273–284. doi: 10.1016/j.enpol.2014.01.027.

Barbat, A. H. *et al.* (2010) 'Seismic vulnerability and risk evaluation methods for urban areas. A review with application to a pilot area', *Structure and Infrastructure Engineering*, 6(1–2), pp. 17–38. doi: 10.1080/15732470802663763.

Barbat, A. H., Moya, F. Y. and Canas, J. A. (1996) 'Damage scenarios simulation for seismic risk assessment in urban zones', *Earthquake Spectra*, 12(3), pp. 371–394. doi: 10.1193/1.1585889.

Bazzurro, P. *et al.* (1998) 'Three Proposals for Characterizing MDOF Nonlinear Seismic Response', *Journal of Structural Engineering*, 124(11), pp. 1281–1289. doi: 10.1061/(asce)0733-9445(1998)124:11(1281).

Bazzurro, P. and Cornell, C. (1995) 'Seismic hazard analysis of nonlinear structures. I: methodology', *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 32(5), p. A240. doi: 10.1016/0148-9062(95)93437-t.

Belleri, A. and Marini, A. (2016) 'Does seismic risk affect the environmental impact of existing buildings ?', *Energy & Buildings*, 110, pp. 149–158. doi: 10.1016/j.enbuild.2015.10.048.

Benedetti, D. and Petrini, V. (1984) 'On the seismic vulnerability of masonry buildings: A method of evaluation', in *L'industria delle Costruziobi*, pp. 66–74.

Bertero, V. V (1977) 'Strength and deformation capacities of buildings under extreme environments', *Structural engineering and structural mechanics*, 53(1), pp. 29–79.

Binda, L. and Saisi, A. (2005) 'Research on historic structures in seismic areas in Italy', *Progress in Structural Engineering and Materials*, 7(2), pp. 71–85. doi: 10.1002/pse.194.

Borzi, B., Pinho, R. and Crowley, H. (2008) 'Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings', *Engineering Structures*, 30(3), pp. 804–820. doi: 10.1016/j.engstruct.2007.05.021.

Braga, F. and Dolce, M. (1982) 'Un metodo per l'analisi di edifici multipiano in muratura antisismici', in *6th I.B.Ma.C.* Rome, pp. 1088–1099.

Braga, F., Dolce, M. and Liberatore, D. (1982) 'A statistical study on damaged buildings and an ensuing review of the M.S.K.-76 scale', in *7th European conference on earthquake engineeering, Atene*.

Brzev, S. *et al.* (2013) 'GEM Building Taxonomy Version 2.0', *GEM Technical Report*, 02, p. 188.

Cacace, F. *et al.* (2018) 'Building Inventory at National scale by evaluation of seismic vulnerability classes distribution based on Census data analysis: BINC procedure', *International Journal of Disaster Risk Reduction*, 28(March), pp. 384–393. doi: 10.1016/j.ijdrr.2018.03.016.

Cajot, S. *et al.* (2017) 'Obstacles in energy planning at the urban scale', *Sustainable Cities and Society*, 30, pp. 223–236. doi: 10.1016/j.scs.2017.02.003.

Calvi, G. M. *et al.* (2006) 'Developement of seismic vulnerability assessment methodologies over the past 30 years', *ISET Journal of Earthquake Technology, Paper No. 472*, 43(3), pp. 75–104. Available at: https://pdfs.semanticscholar.org/ff47/e72c838a6cba9227fa54d2b622da160b295e.pdf.

Calvi, G. M., Sousa, L. S. and Ruggeri, C. (2016) 'Energy Efficiency and Seismic Resilience: A Common Approach', in *Multi-Hazard Approaches to Civil Infrastructure Engineering*, pp. 1–573. doi: 10.1007/978-3-319-29713-2.

Caputo, P., Costa, G. and Ferrari, S. (2013) 'A supporting method for defining energy strategies in the building sector at urban scale', *Energy Policy*, 55, pp. 261–270. doi: 10.1016/j.enpol.2012.12.006.

Cara, S. *et al.* (2018) 'Seismic Risk Assessment and Mitigation at Emergency Limit Condition of Historical Buildings along Strategic Urban Roadways. Application to the "Antiga Esquerra de L'Eixample" Neighborhood of Barcelona', *International Journal of Architectural Heritage*, 12(7–8), pp. 1055–1075. doi: 10.1080/15583058.2018.1503376.

Casolo, S. *et al.* (2017) 'Seismic modelling and analysis of masonry building in aggregate: A case study', *COMPDYN 2017 - Proceedings of the 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 1, pp. 2619–2638. doi: 10.7712/120117.5593.18376.

Cerezo, C., Dogan, T. and Reinhart, C. (2014) 'Towards standarized building properties template files for early design energy model generation', *2014 ASHRAE/IBPSA-USA Building Simulation Conference*, pp. 25–32.

Cheung, M., Foo, S. and Granadino, J. (2000) 'Seismic retrofit of existing buildings: innovative alternatives', *Public works and government …*, pp. 1–10. Available at: http://www.ironwarrior.org/ARE/Lateral_Forces/Cheung-M Seismic Retrofits.pdf.

Chopra, A. K. and Chintanapakdee, C. (2004) 'Evaluation of Modal and FEMA Pushover Analyses: Vertically "Regular" and Irregular Generic Frames', *Earthquake Spectra*, 20(1), pp. 255–271. doi: 10.1193/1.1647580.

Choudhury, T. and Kaushik, H. B. (2018) 'Seismic Response Sensitivity to Uncertain Variables in RC Frames with Infill Walls', *Journal of Structural Engineering*, 144(10), p. 04018184. doi: 10.1061/(asce)st.1943-541x.0002190.

Circolare NTC18 (2019) 'Circolare 21 gennaio 2019 n.7 " Istruzioni per l'applicazione dell'«Aggiornamento delle "Norme tecniche per le costruzioni"» di cui al decreto ministeriale 17 gennaio 2018"', *Ministero delle Infrastrutture*. Available at: https://www.gazzettaufficiale.it/eli/gu/2019/02/11/35/so/5/sg/pdf.

Corsanego, A. and Petrini, V. (1990) 'Seismic Vulnerability of Buildings – Work in Progress."', *Proceedings of Workshop II on Seismic Risk Vulnerability and Risk Assessment, Trieste, Italy*, pp. 10–14.

Crowley, H. *et al.* (2012) 'Development of a European building inventory database', *15th World Conference on Earthquake Engineering*, pp. 24–28.

Dall'o', G., Galante, A. and Torri, M. (2012) 'A methodology for the energy performance classification of residential building stock on an urban scale', *Energy and Buildings*, 48, pp. 211–219. doi: 10.1016/j.enbuild.2012.01.034.

Dall'O', G., Galante, A. and Torri, M. (2012) 'A methodology for the energy performance classification of residential building stock on an urban scale', *Energy and Buildings*. doi: 10.1016/j.enbuild.2012.01.034.

'DI 192-2015' (2015) *Decreto interministeriale 26 giugno 2015 Decreto interministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici.*

Dogan, T. and Reinhart, C. (2013) 'Automated conversion of architectural massing models into thermal "shoebox" models', *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, pp. 3745–3752.

Dolce, M. (1989) ‘Schematizzazione e modellazione per azioni nel piano delle pareti, Corso sul “Consolidamento degli edifici in muratura in zona sismica”, Ordine degli Ingegneri’, in. Potenza.

Dolce, M. *et al.* (2003) ‘Earthquake damage scenarios of the building stock of Potenza (Southern Italy) including site effects. , 1(1), .’, *Bulletin of Earthquake Engineering*, 1(1), pp. 115–140.

Dolce, M. *et al.* (2020) ‘Seismic risk assessment of residential buildings in Italy’, *Bulletin of Earthquake Engineering*. doi: 10.1007/s10518-020-01009-5.

Dolce, M. and Goretti, A. (2005) ‘Building damage assessment after the 2009 Abruzzi earthquake’, *Bulletin of Earthquake Engineering*, 13(8).

Dolce, M., Zuccaro, G. and Papa, F. (2002) ‘Protocollo d’intervista. Dipartimento della Protezione Civile’.

DPR n. 412 (no date). Available at: http://www.normattiva.it/do/atto/caricaRiferimentiURNFull?atto.dataPubblicazioneGazzetta=2012-08-10&atto.codiceRedazionale=012G0156&atto.giornoVigenza=30&atto.meseVigenza=12&atto.annoVigenza=2012.

Eicker, U. *et al.* (2014) ‘Assessing passive and active solar energy resources in cities using 3D city models’, *Energy Procedia*, 57, pp. 896–905. doi: 10.1016/j.egypro.2014.10.299.

Elnashai, M. A. and Erberik, A. S. (2003) ‘Technical Report Mid-America earthquke center DS-9 project’.

Escobar-Wolf, R. *et al.* (2021) ‘A GIS Tool for Infinite Slope Stability Analysis (GIS-TISSA)’, *Geoscience Frontiers*, 12(2), pp. 756–768. doi: 10.1016/j.gsf.2020.09.008.

Fagundes, C., Bento, R. and Cattari, S. (2017) ‘On the seismic response of buildings in aggregate: Analysis of a typical masonry building from Azores’, *Structures*, 10, pp. 184–196. doi: 10.1016/j.istruc.2016.09.010.

Famuyibo, A. A., Duffy, A. and Strachan, P. (2012) ‘Developing archetypes for domestic dwellings - An Irish case study’, *Energy and Buildings*, 50, pp. 150–157. doi: 10.1016/j.enbuild.2012.03.033.

Federal Emergency Management Agency (FEMA) (2003) *HAZUS-MH MR4 Technical Manual*, *National Institute of Building Sciences and Federal Emergency Management Agency (NIBS and FEMA)*. Washington.

FEMA (1997) *FEMA. FEMA273, NEHRP Guidelines for the seismic rehabilitation of buildings*.

FEMA (2001) 'HAZUS99 Technical Manual', in. Washington, D.C., USA.

FEMA, P. (2009) *Commentary for the Seismic Rehabilitation of Buildings*, *FEMA-356, Federal Emergency Management Agency, Washington, DC*.

Firth, S. K. and Lomas, K. J. (2009) 'Investigating CO2 emission reductions in existing urban housing using a community domestic energy model', *IBPSA 2009 - International Building Performance Simulation Association 2009*, pp. 2098–2105.

Fonseca, J. A. and Schlueter, A. (2015) 'Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts', *Applied Energy*, 142, pp. 247–265. doi: 10.1016/j.apenergy.2014.12.068.

Formisano, A. *et al.* (2015) 'Numerical calibration of an easy method for seismic behaviour assessment on large scale of masonry building aggregates', *Advances in Engineering Software*, 80(C), pp. 116–138. doi: 10.1016/j.advengsoft.2014.09.013.

Formisano, A. (2017) 'Theoretical and Numerical Seismic Analysis of Masonry Building Aggregates: Case Studies in San Pio Delle Camere (L'Aquila, Italy)', *Journal of Earthquake Engineering*, 21(2), pp. 227–245. doi: 10.1080/13632469.2016.1172376.

Fragiadakis, M. and Vamvatsikos, D. (2010) 'Fast performance uncertainty estimation via pushover and approximate IDA', *Earthquake Engineering and Structural Dynamics*, 39(6), pp. 683–703. doi: 10.1002/eqe.965.

Frassine, L. and Giovinazzi, S. (2004) 'Basi di dati a confronto nell ' analisi di vulnerabilità sismica dell ' edilizia residenziale : un ' applicazione per la città di Catania', *ANIDIS XI Congresso Nazionale Lingegneria Sismica in Italia*, p. 16.

Frayssinet, L. *et al.* (2018) 'Modeling the heating and cooling energy demand of urban buildings at city scale', *Renewable and Sustainable Energy Reviews*, 81(March 2016), pp. 2318–2327. doi: 10.1016/j.rser.2017.06.040.

Freire, S. *et al.* (2010) 'Extraction of buildings from QuickBird imagery for municipal planning purposes: quality assessment considering existing mapping standards', in *30 EARsel symposium: remote sensing for science, education and culture*. Paris.

Gamba, P., Dell'Acqua, F., & Lisini, G. (2009) 'BREC: the Built-up area RECognition tool', in *Urban Remote Sensing Event*.

Gambarotta, L. and Lagomarsino, S. (1997) 'Damage models for the seismic response of brick masonry shear walls. Part I: The mortar joint model and its applications', *Earthquake Engineering and Structural Dynamics*, 26(4), pp. 423–439. doi: 10.1002/(sici)1096-9845(199704)26:4<423::aid-eqe650>3.0.co;2-%23.

Del Gaudio, C. *et al.* (2015) 'Development and urban-scale application of a simplified method for seismic fragility assessment of RC buildings.', *Engineering Structures*, 91, pp. 40–57.

Giovinazzi, S. and Lagomarsino, S. (2001) 'Una metodologia per l'analisi di vulnerabilità sismica del costruito', *X Congresso Nazionale 'L'Ingegneria Sismica in Italia' - ANIDIS*.

Giuffrè, A. (1993) *Safety and conservation of historical centers: the Ortigia case*. Editori La, *Editori Laterza: Bari*. Editori La. Roma Bari.

GNDT, T. G. N. P. la D. dai (1993) 'Rischio sismico di edifici pubblici'.

Goel, R. K. and Chopra, A. K. (2004) 'Evaluation of Modal and FEMA Pushover Analyses: SAC Buildings', *Earthquake Spectra*, 20(1), pp. 225–254. doi: 10.1193/1.1646390.

Gracik, S. *et al.* (2015) 'Effect of urban neighborhoods on the performance of building cooling systems', *Building and Environment*, 90, pp. 15–29. doi: 10.1016/j.buildenv.2015.02.037.

La Greca, P. and Margani, G. (2018) 'Seismic and energy renovation measures for sustainable cities: A critical analysis of the Italian scenario', *Sustainability (Switzerland)*, 10(1), p. 254. doi: 10.3390/su10010254.

Grünthal, G. (1998) *European Macroseismic Scale 1998*, *Comisión Sismológica Europea*. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:European+Macroseismic+Scale+1998#0.

Guéguen, P., Michel, C. and Lecorre, L. (2007) 'A simplified approach for vulnerability assessment in moderate-to-low seismic hazard regions: Application to Grenoble (France)', *Bulletin of Earthquake Engineering*, 5(3), pp. 467–490. doi: 10.1007/s10518-007-9036-3.

Hansapinyo, C., Latcharote, P. and Limkatanyu, S. (2020) 'Seismic Building Damage Prediction From GIS-Based Building Data Using Artificial Intelligence System', *Frontiers in Built Environment*, 6. doi: 10.3389/fbuil.2020.576919.

Hassan, A. F. and Sozen, M. A. (1997) 'Seismic vulnerability assessment of low-rise buildings in regions with infrequent earthquakes', *ACI Structural Journal*, 94(1), pp. 31–39. doi: 10.14359/458.

Holmes, W. (2010) 'Progress of Seismic Rehabilitation of Buildings in the US. Improving the Seismic Performance of Existing Buildings and Other Structures'.

Indirli, M. (2009) 'Organization of a geographic information system (GIS) database on natural hazards and structural vulnerability for the historic center of San Giuliano di Puglia (Italy) and the city of Valparaiso (Chile)', *International Journal of Architectural Heritage*, 3(4), pp. 276–315. doi: 10.1080/15583050902803780.

ISTAT (2011) *15° Censimento generale della popolazione e delle abitazioni - 9 ottobre 2011*. Available at: http://istat.it/MD/.

Jalayer, F., De Risi, R. and Manfredi, G. (2015) 'Bayesian Cloud Analysis: Efficient structural fragility assessment using linear regression', *Bulletin of Earthquake Engineering*, 13(4), pp. 1183–1203. doi: 10.1007/s10518-014-9692-z.

Jiménez, B., Pelà, L. and Hurtado, M. (2018) 'Building survey forms for heterogeneous urban areas in seismically hazardous zones. Application to the historical center of Valparaíso, Chile', *International Journal of Architectural Heritage*, 12(7–8), pp. 1076–1111. doi: 10.1080/15583058.2018.1503370.

Kappos, A. *et al.* (1995) 'Cost-benefit analysis for the seismic rehabilitation of buildings in Thessaloniki, based on a hybrid method of vulnerability assessment', *Proceedings of the 5th International Conference on Seismic Zonation*, 1, pp. 406–413.

Kappos, A. J., Stylianidis, K. C. and Pitilakis, K. (1998) 'Development of seismic risk scenarios based on a hybrid method of vulnerability assessment', *Natural Hazards*, 17(2), pp. 177–192. doi: 10.1023/A:1008083021022.

Kassem, M. M., Mohamed Nazri, F. and Noroozinejad Farsangi, E. (2020) 'The seismic vulnerability assessment methodologies: A state-of-the-art review', *Ain Shams Engineering Journal*, 11(4), pp. 849–864. doi: 10.1016/j.asej.2020.04.001.

Khan, M. (2020) 'Modelling of Seismicity in Southern Pakistan using GIS Techniques'. doi: 10.21203/rs.3.rs-27523/v1.

Kim, E. J. *et al.* (2014) 'Urban energy simulation: Simplification and reduction of building envelope models', *Energy and Buildings*, 84, pp. 193–202. doi: 10.1016/j.enbuild.2014.07.066.

Kim, H. S. *et al.* (2020) 'GIS-based optimum geospatial characterization for seismic site effect assessment in an inland urban area, South Korea', *Applied Sciences*

(Switzerland), 10(21), pp. 1–24. doi: 10.3390/app10217443.

Kolter, J. Z. and Ferreira, J. (2011) 'A large-scale study on predicting and contextualizing building energy usage', *Proceedings of the National Conference on Artificial Intelligence*, 2, pp. 1349–1356.

Krawinkler, H., Medina, R. and Alavi, B. (2003) 'Seismic drift and ductility demands and their dependence on ground motions', *Engineering Structures*, 25(5), pp. 637–653. doi: 10.1016/S0141-0296(02)00174-8.

Kunnath, S. K. and Gupta, B. (2000) 'Adaptive Spectra-Based Pushover Procedure for Seismic Evaluation of Structures', *Earthquake Spectra*, 16(2), pp. 367–391.

Lagomarsino, S. and Giovinazzi, S. (2006) 'Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings', *Bulletin of Earthquake Engineering*, 4(4), pp. 415–443. doi: 10.1007/s10518-006-9024-z.

Lang, D. H. *et al.* (2018) 'Building typology classification and earthquake vulnerability scale of Central and South Asian building stock', *Journal of Building Engineering*, 15, pp. 261–277. doi: 10.1016/j.jobe.2017.11.022.

Li, W. *et al.* (2017) 'Modeling urban building energy use: A review of modeling approaches and procedures', *Energy*, 141, pp. 2445–2457. doi: 10.1016/j.energy.2017.11.071.

Lin, T. and Baker, J. W. (2013) 'Introducing adaptive incremental dynamic analysis: A new tool for linking ground motion selection and structural response assessment', *Safety, Reliability, Risk and Life-Cycle Performance of Structures and Infrastructures - Proceedings of the 11th International Conference on Structural Safety and Reliability, ICOSSAR 2013*, pp. 805–811.

Liu, Y. *et al.* (2019) 'Seismic vulnerability assessment at urban scale using data mining and GIScience technology: application to Urumqi (China)', *Geomatics, Natural Hazards and Risk*, 10(1), pp. 958–985. doi: 10.1080/19475705.2018.1524400.

Liu, Y. and Kuang, J. S. (2017) 'Spectrum-based pushover analysis for estimating seismic demand of tall buildings', *Bulletin of Earthquake Engineering*, 15(10), pp. 4193–4214. doi: 10.1007/s10518-017-0132-8.

Maio, R. *et al.* (2018) 'Investigation Techniques for the Seismic Response Assessment of Buildings Located in Historical Centers', *International Journal of Architectural Heritage*, 12(7–8), pp. 1245–1258. doi: 10.1080/15583058.2018.1503363.

Maison, B. F. and Bonowitz, D. (2004) ‘Discussion of “Seismic Performance Evaluation of Pre-Northridge Steel Frame Buildings with Brittle Connections” by Kihak Lee and Douglas A. Foutch’, *Journal of Structural Engineering*, 130(4), pp. 690–691. doi: 10.1061/(asce)0733-9445(2004)130:4(690).

Manfredi, V. (2018) ‘Seismic Strengthening and Energy Efficiency : Towards an Integrated Approach for the Rehabilitation of Existing RC Buildings’. doi: 10.3390/buildings8030036.

Masi, A. (2003) ‘Seismic Vulnerability Assessment of Gravity Load Designed R/C Frames’, *Bulletin of Earthquake Engineering,* 1(3), pp. 371–395.

Matassoni, L. *et al.* (2013) ‘Computational Science and Its Applications – ICCSA 2013’, 7974, pp. 278–293. doi: 10.1007/978-3-642-39649-6.

De Matteis, G. and Zizi, M. (2019) ‘Seismic Damage Prediction of Masonry Churches by a PGA-based Approach’, *International Journal of Architectural Heritage*, 13(7), pp. 1165–1179. doi: 10.1080/15583058.2019.1597215.

Medvedev, S. W., Sponheuer, W. and Karnik, V. (1965) ‘Seismic intensity scale version MSK 1964’, *Working group on seismicity and seismo-tectonics, First meeting, Tbilissi, 8-12June 1965*, p. 7.

Meroni, F. *et al.* (2017) ‘Damage Scenario for the 2012 Northern Italy Earthquakes and Estimation of the Economic Losses to Residential Buildings’, *International Journal of Disaster Risk Science*, 8(3), pp. 326–341.

Milutinovic, Z. and Trendafiloski, G. (2003) ‘Risk-UE An advanced approach to earthquake risk scenarios with applications to different european towns’, *Report to WP4: vulnerability of current buildings*, (December), pp. 1–83. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:An+advanced+approach+to+earthquake+risk+scenarios+with+applications+to+different+European+towns#0.

Ministero dei lavori pubblici (1981) *Decreto Ministeriale 7 Marzo 1981 “Dichiarazione in zone sismiche nelle regioni Basilicata, Campania e Puglia”*.

Ministero delle Infrastrutture e dei Trasporti (2018) *Aggiornamento delle ‘Norme tecniche per le costruzioni’ (in Italian)*.

Ministry of Cultural Heritage and Activities (2010) ‘Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale’.

Miranda, E. (1999) ‘Approximate Seismic Lateral Deformation Demands in

Multistory Buildings', *Journal of Structural Engineering*, 125(4), pp. 417–425. doi: 10.1061/(asce)0733-9445(1999)125:4(417).

Miura, H. and Midorikawa, S. (2006) 'Updating GIS building inventory data using high-resolution satellite images for earthquake damage assessment: application to metro Manila, Philippines', *Earthquake spectra*, 22(1), pp. 151–168.

Monteiro, R. *et al.* (2016) 'Towards integrated seismic risk assessment in Palestine - Application to the city of Nablus', *ECCOMAS Congress 2016 - Proceedings of the 7th European Congress on Computational Methods in Applied Sciences and Engineering*, 3, pp. 5987–5998. doi: 10.7712/100016.2235.12031.

Mosalam, K. M. *et al.* (2014) 'Performance-Based Engineering Approach To the Best Decision for Energy – Efficient and Sustainable Building Design', (December), pp. 121–133.

Mosalam, K. M. *et al.* (2018) 'Performance-based engineering and multi-criteria decision analysis for sustainable and resilient building design', *Structural Safety*, 74, pp. 1–13. doi: 10.1016/j.strusafe.2018.03.005.

Mouroux, P. *et al.* (2004) 'The European RISK-UE project: an advanced approach to earthquake risk scenarios', in *13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 3329 THE*, p. 3329.

Mueller, M. *et al.* (2006) 'Potential of high-resolution satellite data in the context of vulnerability of buildings. 2006. Natural hazards, 38(1-2), 247-258.', 38(1–2), pp. 247–258.

National Institute of Building Sciences (NIBS) (1999) *HAZUS User's Manual, prepared for Federal Emergency Management Agency*. Washington D.C.

'Newsoft POR2000. Structural and seismic calculation and analysis of masonry structures' (2020).

NZSFE (2014) *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes: Prioritisation, Initial Evaluation, Detailed Assessment, Improvement Measures: Recommendations of a NZSEE Study Group on Earthquake Risk Buildings New Zealand Society fo*.

O.P.C.M. n. 3431 (2005) 'Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica'.

Opcm n. 3274 del 20 marzo 2003: primi elementi in materia di criteri generali per *la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica* (2003).

Orsini, G. (1999) 'A model for buildings' vulnerability assessment using the parameterless scale of seismic intensity (PSI)', *Earthquake Spectra*, 15(3), pp. 463–483. doi: 10.1193/1.1586053.

Otani, S. (2000) 'Seismic Vulnerability Assessment Methods for Buildings in Japan', *Earthquake Engineering and Engineering Seismology*, 2(2), pp. 47–56.

Pagnini, L. C. *et al.* (2011) 'A mechanical model for the seismic vulnerability assessment of old masonry buildings', *Earthquake and Structures*, 2(1), pp. 25–42. doi: 10.12989/eas.2011.2.1.025.

Park, H. S., Hwang, J. W. and Oh, B. K. (2018) 'Integrated analysis model for assessing CO2 emissions, seismic performance, and costs of buildings through performance-based optimal seismic design with sustainability', *Energy and Buildings*, 158, pp. 761–775. doi: 10.1016/j.enbuild.2017.10.070.

Park, Y. J. and Ang, A. H. S. (1985) 'Mechanistic Seismic Damage Model for Reinforced Concrete', *Journal of Structural Engineering*, 111(4), pp. 722–739.

Di Pasquale, G., Orsini, G. and Romeo, R. W. (2005) 'New developments in seismic risk assessment in Italy', *Bulletin of Earthquake Engineering*, 3(1), pp. 101–128. doi: 10.1007/s10518-005-0202-1.

Pelà, L. (2018) 'New Trends and Challenges in Large-Scale and Urban Assessment of Seismic Risk in Historical Centres', *International Journal of Architectural Heritage*, 12(7–8), pp. 1051–1054. doi: 10.1080/15583058.2018.1520858.

Perrone, D. *et al.* (2015) 'Rapid visual screening for seismic evaluation of RC hospital buildings', *ISTRUC*. doi: 10.1016/j.istruc.2015.03.002.

Pitilakis, K. *et al.* (2014) 'SYNER-G: Systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities: Methodology and Applications', *Geotechnical, Geological and Earthquake Engineering*, 31.

Polese, M., Gaetani d'Aragona, M. and Prota, A. (2019) 'Simplified approach for building inventory and seismic damage assessment at the territorial scale: An application for a town in southern Italy', *Soil Dynamics and Earthquake Engineering*, 121(April), pp. 405–420. doi: 10.1016/j.soildyn.2019.03.028.

Polese, M., Di Ludovico, M. and Prota, A. (2018) 'Post-earthquake reconstruction:

a study on the factors influencing demolition decisions after 2009 L'Aquila earthquake', *Soil dynamics and earthquake engineering*, 105, pp. 139–149.

Polli, D., Dell'Acqua, F. and Gamba, P. (2009) 'First steps towards a framework for earth observation (EO)-based seismic vulnerability evaluation', *Environmental Semeiotics*, 2(1), pp. 16–30.

Pons, O. and Aguado, A. (2012) 'Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain', *Building and Environment*, 53, pp. 49–58. doi: 10.1016/j.buildenv.2012.01.007.

Qiong-Lin, L., Zhi-Ping, L. and Si-Yi, C. (2020) 'Analysis of the Morphological Characteristics of Canton Postal ArchitecturalLayout from 1842 to 1949 on GIS', *IOP Conference Series: Earth and Environmental Science*, 525(1). doi: 10.1088/1755-1315/525/1/012106.

Ramos, L. F. and Lourenço, P. B. (2004) 'Modeling and vulnerability of historical city centers in seismic areas: A case study in Lisbon', *Engineering Structures*, 26(9), pp. 1295–1310. doi: 10.1016/j.engstruct.2004.04.008.

'Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook' (2003) *Disaster Prevention and Management: An International Journal*, 12(4). doi: 10.1108/dpm.2003.07312dab.014.

Reinhart, C. F. and Cerezo Davila, C. (2016) 'Urban building energy modeling - A review of a nascent field', *Building and Environment*, 97, pp. 196–202. doi: 10.1016/j.buildenv.2015.12.001.

ReLUIS (2010) 'Linee guida per il rilievo, l'analisi ed il progetto di interventi di riparazione e consolidamento sismico di edifici in muratura in aggregato', 3, p. 105.

Riedel I., Guéguen P., Dalla Mura M., Pathier E., Leduc T., C. J. (2015) 'Seismic Vulnerability assessment of urban environments in moderate-to-low seismic hazard regions using association rule learning and support vector machine methods', *Natural Hazards*, 76(2), pp. 1111–1141.

Riedel, I. *et al.* (2014) 'Macro-scale vulnerability assessment of cities using Association Rule Learning', *Seismological Research Letters*, 85(2), pp. 295–305.

Riks, E. (1979) 'An incremental approach to the solution of snapping and buckling problems', *International Journal of Solids and Structures*, 15(7), pp. 529–551.

Rizzano, G. (2011) 'A Simplified Approach for the Seismic Analysis of Masonry Structures', *The Open Construction and Building Technology Journal*, 5(1), pp. 97–

104. doi: 10.2174/1874836801105010097.

Robinson, D. and Stone, A. (2004) 'Comprehensive Micro-Simulation of Resource Flows for Sustainable Urban Planning', *Sol Energy*.

Roca, P., Universidad Politécnica de Catalunya. Centre Internacional de Mèthodes Numèrics en Enginyeria. and International Seminar on Structural Analysis of Historical Constructions (1995 : Barcelona, S. (1997) 'Structural analysis of historical constructions : possibilities of numerical and experimental techniques', p. 407. Available at: http://www.cimne.com/tiendacimne/book.asp?id_prod=140.

Rossetto, T. and Elnashai, A. (2005) 'A new analytical procedure for the derivation of displacement-based vulnerability curves for populations of RC structures', *Engineering Structures*, 27(3), pp. 397–409. doi: 10.1016/j.engstruct.2004.11.002.

Rota, M., Penna, A. and Magenes, G. (2010) 'A methodology for deriving analytical fragility curves for masonry buildings based on stochastic nonlinear analyses', *Engineering Structures*, 32(5), pp. 1312–1323. doi: 10.1016/j.engstruct.2010.01.009.

Rota, M., Penna, A. and Strobbia, C. (2006) 'Typological Fragility Curves From Italian Earthquake Damage Data', *Conference on Earthquake*, (September), pp. 3–8.

Saatcioglu, M., Shooshtari, M. and Foo, S. (2013) 'Seismic screening of buildings based on the 2010 National Building Code of Canada1', *Canadian Journal of Civil Engineering*, 40(5), pp. 483–498. doi: 10.1139/cjce-2012-0055.

Sabetta, F. and Pugliese, a (1987) 'Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records', *Bulletin of the Seismological Society of …*, 77(5), pp. 1491–1513. Available at: http://www.bssaonline.org/content/77/5/1491.short.

Saltelli, A. *et al.* (2004) *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models*. John Wiley.

Senaldi, I., Magenes, G. and Penna, A. (2010) 'Numerical investigations on the seismic response of masonry building aggregates', *Advanced Materials Research*, 133–134, pp. 715–720. doi: 10.4028/www.scientific.net/AMR.133-134.715.

Shafei, B., Zareian, F. and Lignos, D. G. (2011) 'A simplified method for collapse capacity assessment of moment-resisting frame and shear wall structural systems', *Engineering Structures*, 33(4), pp. 1107–1116. doi: 10.1016/j.engstruct.2010.12.028.

Shome, N. (1999) 'Probabilistic seismic demand analysis of nonlinear structures', p. 320.

Singhal, A. and Kiremidjian, A. S. (1996) ‘Method for Probabilistic Evaluation of Seismic Structural Damage’, *Journal of Structural Engineering*, 122(12), pp. 1459–1467.

Singhal, A. and Kiremidjian, A. S. (1998) ‘Bayesian Updating of Fragilities with Application to RC Frames’, *Journal of Structural Engineering*, 124(8).

Sobol’, I. M. *et al.* (2007) ‘Estimating the approximation error when fixing unessential factors in global sensitivity analysis’, *Reliability Engineering and System Safety*, 92, pp. 950–960.

Sobol′, I. M. (1993) ‘Sensitivity estimates for nonlinear mathematical models’, *Mathematical Modelling and Computational Experiment*, 1(4), pp. 407–414.

Spence, R., Coburn, A. W. and Pomonis, A. (1992) ‘Correlation of Ground Motion with Building Damage: The Definition of a New Damage-Based Seismic Intensity Scale’, in *Tenth World Conference on Earthquake Engineering*. Madrid, pp. 551–556.

Swan, L. G. and Ugursal, V. I. (2009) ‘Modeling of end-use energy consumption in the residential sector : A review of modeling techniques’, 13, pp. 1819–1835. doi: 10.1016/j.rser.2008.09.033.

TABULA Project Team (2012) ‘Typology Approach for Building Stock Energy Assessment - Main Results of the TABULA project’, (June 2009), p. 43. Available at: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/tabula_final_report_en.pdf.

Taffarel, S. *et al.* (2016) ‘Seismic vulnerability maps of Timisoara historical center based on fragility curves’, *Structural Analysis of Historical Constructions: Anamnesis, diagnosis, therapy, controls - Proceedings of the 10th International Conference on Structural Analysis of Historical Constructions, SAHC 2016*, pp. 1605–1612. doi: 10.1201/9781315616995-217.

Tomazevic, M. (1978) *The computer program POR. Report ZRMK*. Ljubljana.

Toparlar, Y. *et al.* (2015) ‘CFD simulation and validation of urban microclimate: A case study for Bergpolder Zuid, Rotterdam’, *Building and Environment*, 83, pp. 79–90. doi: 10.1016/j.buildenv.2014.08.004.

Torabi Moghadam, S. *et al.* (2018) ‘A GIS-statistical approach for assessing built environment energy use at urban scale’, *Sustainable Cities and Society*, 37(October 2017), pp. 70–84. doi: 10.1016/j.scs.2017.10.002.

Uni, 10349 (2016) ‘CTI- Riscaldamento e raffrescamento degli edifici. Dati climatici', p. 35.

Uva, G. *et al.* (2016) 'ANTAEUS Project for the Regional Vulnerability Assessment of the Current Building Stock in Historical Centers', *International Journal of Architectural Heritage*. doi: 10.1080/15583058.2014.935983.

Uva, G. *et al.* (2017) 'Modelling Framework for Sustainable Co-management of Multi-purpose Exhibition Systems: The "fiera del Levante" Case', in *Procedia Engineering*. doi: 10.1016/j.proeng.2017.04.242.

Uva, G., Ciampoli, P. L., *et al.* (2019) 'A mechanical approach for estimating regional fragility curves of existing RC buildings stock in Puglia', in *COMPDYN 2019 7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*.

Uva, G., Leggieri, V., *et al.* (2019) 'Simplified integrated assessment of the structural and energy performance of existing buildings at the urban scale: a case study in Puglia, Italy', in *3rd International Conference on International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation Structures, CoRASS 2019, Coimbra,*.

Uva, G., Iannone, F. and Leggieri, V. (2019) 'Integrated assessment of energy performance and seismic vulnerability of existing building stock at urban scale through BIM: An application to "Fiera del Levante"', *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, 2019-Octob, pp. 964–969. doi: 10.1109/SMC.2019.8913920.

Uva, G., Leggieri, V. and Mastrodonato, G. (2019) 'Proposal of a procedure for gathering data for the structural and energy classification of residential building stock: a case study in Puglia', in *3rd International Conference on International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation Structures, CoRASS 2019, Coimbra*.

Uva, G., Leggieri, V. and Morrone, M. (2019) 'Use of data derived by different sources for the seismic vulnerability assessment of current building stock in GIS environment: an application to the municipality of Bisceglie, Italy', in *3rd International Conference on International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation Structures, CoRASS 2019, Coimbra*.

Vamvatsikos, D. and Cornell, C. A. (2004) 'Applied incremental dynamic analysis', *Earthquake Spectra*, 20(2), pp. 523–553. doi: 10.1193/1.1737737.

Vicente, R. *et al.* (2011) 'Seismic vulnerability and risk assessment: Case study of the historic city centre of Coimbra, Portugal', *Bulletin of Earthquake Engineering*, 9(4), pp. 1067–1096. doi: 10.1007/s10518-010-9233-3.

Vona, M. (2014) 'Fragility Curves of Existing RC Buildings Based on Specific Structural Performance Levels', *Open Journal of Civil Engineering*, 04(02), pp. 120–134. doi: 10.4236/ojce.2014.42011.

Vona, M. *et al.* (2017) 'Characterization of URM buildings and evaluation of damages in a historical center for the seismic risk mitigation and emergency management', *International Journal of Disaster Risk Reduction*, 24, pp. 251–263. doi: 10.1016/j.ijdrr.2017.05.008.

Wallace, N. M. and Miller, T. H. (2008) 'Seismic Screening of Public Facilities in Oregon's Western Counties', *Practice Periodical on Structural Design and Construction*, 13(4), pp. 189–197. doi: 10.1061/(asce)1084-0680(2008)13:4(189).

Whitman, R. V. *et al.* (1997) 'Development of a national earthquake loss estimation methodology', *Earthquake Spectra*, 13(4), pp. 643–661. doi: 10.1193/1.1585973.

Yakut, A. (2004) 'Preliminary seismic performance assessment procedure for existing RC buildings', *Engineering Structures*, 26(10), pp. 1447–1461. doi: 10.1016/j.engstruct.2004.05.011.

Yun, S.-Y. *et al.* (2002) 'Seismic Performance Evaluation for Steel Moment Frames', *Journal of Structural Engineering*, 128(4), pp. 534–545. doi: 10.1061/(asce)0733-9445(2002)128:4(534).

Zacharenaki, A. E., Fragiadakis, M. and Papadrakakis, M. (2013) 'Reliability-based optimum seismic design of structures using simplified performance estimation methods', *Engineering Structures*, 52, pp. 707–717. doi: 10.1016/j.engstruct.2013.03.007.

Zameeruddin, M. and Sangle, K. K. (2016) 'Review on Recent developments in the performance-based seismic design of reinforced concrete structures', *Structures*, 6, pp. 119–133. doi: 10.1016/j.istruc.2016.03.001.

Zanazzi, E., Coïsson, E. and Ferretti, D. (2019) 'Gis analysis of the seismic damage on historical masonry spires', *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W11), pp. 1173–1179. doi: 10.5194/isprs-Archives-XLII-2-W11-1173-2019.

Zhang, J. Z., Jiang, J. and Li, G. Q. (2017) 'An improved consecutive modal pushover procedure for estimating seismic demands of multi-storey framed buildings', *Structural Design of Tall and Special Buildings*, 26(4). doi: 10.1002/tal.1336.

Zuccaro, G. *et al.* (2016) 'La Scheda Cartis Per La Caratterizzazione Tipologico-Strutturale Dei Comparti Urbani Costituiti Da Edifici Ordinari. Valutazione dell'esposizione in analisi di rischio sismico', *Gngts 2015*, pp. 281–287.

Zuccaro, G. and Cacace, F. (2015) 'Seismic vulnerability assessment based on typological characteristics . The fi rst level procedure " SAVE "', *Soil Dynamics and Earthquake Engineering*, 69, pp. 262–269. doi: 10.1016/j.soildyn.2014.11.003.

Zuccaro, G., Cacace, F. and De Gregorio, D. (2012) 'Buildings inventory for seismic vulnerability assessment on the basis of Census data assessment at national and regional scale', *15th World Conference on Earthquake Engineering*, (SEPTEMBER).

C U R R I C U L U M   V I T A E

INFORMAZIONI PERSONALI

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Nazionalità: ITALIANA

Data di nascita: 22 SETTEMBRE 1987

ESPERIENZA PROFESSIONALE

• Date: Novembre 2017 – Attualmente

• Nome e indirizzo del datore di lavoro: Politecnico di Bari, DICATECh (Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e Chimica), via Edoardo Orabona, 4, 70125, Bari

• Tipo di impiego: PhD Student in “Rischio, Sviluppo Ambientale, Territoriale ed Edilizio” XXXIII Ciclo

• Principali mansioni e responsabilità:

– Attività di ricerca scientifica su metodi di valutazione di vulnerabilità sismica e prestazioni energetiche di edilizia residenziale esistente
– Partecipazione al progetto DPC/Reluis (Dipartimento Protezione Civile) 2014-2018 – Politecnico di Bari, DICATECh: Linea di Ricerca WP2 Rischio implicito per strutture in c.a.; Linea di Ricerca TT1 _ITSEE Inventario delle tipologie strutturali esistenti; UR Politecnico di Bari, Responsabile scientifico: Prof. Ing. Giuseppina Uva
– Partecipazione al progetto DPC/Reluis (Dipartimento Protezione Civile) 2019-2021 – Politecnico di Bari, DICATECh: Linea di Ricerca WP2 Inventario delle tipologie strutturali ed edilizie esistenti-CARTIS; Task 2.1. Schede CARTIS: attività di rilievo e raccolta dati in apposito database; Task 2.3.2. Vulnerabilità delle tipologie in Muratura; Task 2.3.3. Vulnerabilità delle tipologie in Cemento Armato; Task 2.3.6.

Analisi di rischio a scala territoriale; UR Politecnico di Bari, Responsabile scientifico: Prof. Ing. Giuseppina Uva

Co-relatrice per le seguenti tesi di laurea:

– Una metodologia di estrazione, integrazione ed elaborazione di dati multi-sorgente per l'analisi della vulnerabilità a scala urbana: proposte e applicazioni per la città di Taranto
– Una metodologia di estrazione, integrazione ed elaborazione dei dati multi-sorgente per l'analisi della vulnerabilità sismica a scala urbana: proposte e applicazione per il comune di Massafra
– Derivazione di indici di vulnerabilità multicriterio a scala urbana: il caso di studio del comune di Andria in Puglia
– Problemi di modellazione e analisi sismica non lineare di edifici esistenti in c.a.: Il caso di studio di un edificio scolastico a Norcia
– Classi tipologico-strutturali di edifici esistenti in c.a. ed elementi caratteristici di vulnerabilità strutturale e sismica: ricognizione ed analisi nel contesto pugliese
– Vulnerabilità strutturale degli edifici esistenti l'osservazione della vulnerabilità post-sismica in Italia: estrazione ed elaborazione dei database dalla piattaforma Da.D.O
– Vulnerabilità strutturale di serbatoi sopraelevati esistenti in c.a.: approcci di valutazione rapida e casi studio
– Applicazione di approcci indiretti alla analisi di vulnerabilità sismica dell'edilizia residenziale diffusa: il caso del comune di Panni (FG)
– Valutazione di vulnerabilità sismica a scala territoriale dell'edilizia esistente nei centri urbani Pugliesi

• Date	Febbraio 2017 – Ottobre 2017
• Nome e indirizzo del datore di lavoro	Ingegnere MONTANARO Michele, via Cesare Battisti, 174, Taranto
• Tipo di azienda o settore	Ingegneria Civile e Industriale
• Tipo di impiego	Ingegnere Edile collaboratore – Assistente Direzione Lavori Trasformazione strutturale Gallerie Opere di Presa a Mare, ILVA Taranto
• Principali mansioni e responsabilità	– Supervisione dell'esecuzione dei lavori secondo i requisiti imposti dalle condizioni contrattuali e dalle specifiche tecniche – Coordinamento dei vari stakeholder di progetto – Controllo qualitativo e quantitativo dei materiali – Redazione SAL, verbali e documentazione di cantiere – Collaborazione alla progettazione di strutture industriali

• Date	Giugno 2016 – Ottobre 2017
• Nome e indirizzo del datore di lavoro	Studio tecnico Arch. COFANO Giuseppe, via Bolzano 105, Massafra, Taranto
• Tipo di azienda o settore	Edilizia e Urbanistica
• Tipo di impiego	Ingegnere Edile collaboratore
• Principali mansioni e responsabilità	– Progettazione strutturale e architettonica di edilizia residenziale privata – Progettazione di interventi di adeguamento di strutture esistenti in c.a. – Rilievo architettonico – Pratiche edilizie – Certificazione energetica – Redazione PSC, POS, PiMUS
• Date	Settembre 2012 – Gennaio 2013
• Nome e indirizzo del datore di lavoro	Studio tecnico arch. COFANO Giuseppe, via Bolzano 105, Massafra, Taranto
• Tipo di azienda o settore	Edilizia e Urbanistica
• Tipo di impiego	Tirocinante
• Principali mansioni e responsabilità	– Progettazione architettonica di edilizia residenziale privata – Certificazione energetica

ISTRUZIONE E FORMAZIONE

• Date	Gennaio 2017
• Nome e tipo di istituto di istruzione o formazione	Ordine degli Ingegneri di Taranto
• Qualifica conseguita	Iscrizione all'Albo degli Ingegneri della provincia di Taranto al n° 3127 della sezione A – Settore Civile e Ambientale
• Date	Ottobre 2016
• Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, Esame di Stato per l'abilitazione all'esercizio della professione
• Qualifica conseguita	Abilitazione all'esercizio della professione di ingegnere civile e ambientale (sezione A)
• Date	Ottobre 2013 – Aprile 2016
• Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica (DICATECh)
• Qualifica conseguita	Laurea Magistrale in Ingegneria dei Sistemi Edilizi Tesi in Costruzioni in zona sismica e Servizi tecnologici da fonti rinnovabili: "Approccio integrato mediante BIM alla valutazione della

vulnerabilità sismica e delle prestazioni energetiche di edifici esistenti" applicato al caso studio "Fiera del Levante"
Voto: 110/110

• Date	Marzo 2014 – Aprile 2014
• Nome e tipo di istituto di istruzione o formazione	Corso intensivo Erasmus "Sustainable Real Estate Development (SuReEsDe)", Vilnius Gediminas Technical University, Vilnius, Lituania
• Date	Ottobre 2008 – Aprile 2013
• Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica (DICATECh)
• Qualifica conseguita	Laurea di primo livello in Ingegneria Edile Tesi in Architettura tecnica I: "Criteri di progettazione bioclimatica: una casa isolata in zona rurale di Crispiano" Voto: 106/110
• Date	Settembre 2001 – Luglio 2006
• Nome e tipo di istituto di istruzione o formazione	Liceo scientifico "D. de Ruggieri", Massafra, Taranto
• Qualifica conseguita	Diploma di istruzione secondaria superiore ad indirizzo scientifico Voto: 100/100

ATTIVITÀ DI FORMAZIONE

• Date	Febbraio 2017
• Nome e tipo di istituto di istruzione o formazione	Ordine degli Ingegneri di Brindisi
• Qualifica conseguita	Corso di formazione professionale Modellazione Idrologica e Idraulica mediante QGIS ed HEC-RAS

PUBBLICAZIONI

G. Uva, **V. Leggieri**, M. Morrone, G. Mastrodonato, "GIS Multisource data for the seismic vulnerability of the buildings at the urban scale", Structures and Buildings, (under review, submitted in data 01/08/2020)

V. Leggieri, A. di Lernia, G. Elia, D. Raffaele, G. Uva, "Vibrations induced by mechanical rock excavation on R.C. buildings in an urban area", Buildings, Buildings, 2021, 11(1), pp. 1–17, 15 DOI: 10.3390/buildings11010015

G. Uva, **V. Leggieri**, G. Mastrodonato, "Proposal of a procedure for gathering data for the structural and energy classification of residential building stock: a case study in Puglia", 3rd International Conference on International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation of Structures, CoRASS 2019

G. Uva, **V. Leggieri**, M. Morrone, "Use of data derived by different sources for the seismic vulnerability assessment of current building stock in GIS environment: an application to the municipality of Bisceglie, Italy", 3rd International Conference on International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation of Structures, CoRASS 2019

G. Uva, **V. Leggieri**, F. Iannone, S. Casolo, "Simplified integrated assessment of the structural and energy performance of existing buildings at the urban scale: a case study in Puglia, Italy", 3rd International Conference on International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation of Structures, CoRASS 2019

G. Uva, F. Iannone, **V. Leggieri**, "Integrated assessment of energy performance and seismic vulnerability of existing building stock at urban scale through BIM: An application to 'Fiera del Levante'", Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics, 8913920, pp. 964-969, October 2019 DOI: 10.1109/SMC.2019.8913920

G. Uva, V. Sangiorgio, P.L. Ciampoli, **V. Leggieri**, S. Ruggieri, "A novel rapid survey form for the vulnerability assessment of existing building stock based on the 'index building' approach", Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics, 8914063, pp. 976-98, October 2019 DOI: 10.1109/SMC.2019.8914063

G. Uva, P.L. Ciampoli, **V. Leggieri**, S. Ruggieri, "A mechanical approach for estimating regional fragility curves of existing RC buildings stock in Puglia", COMPDYN 2019 7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering Proceedings, Creta, Greece, 24 – 26 Giugno 2019 DOI: 10.7712/120119.7027.19153

M. Dassisti, G. Uva, F. Iannone, G. Florio, F. Maddalena, M. Ruta, A. Grieco, I. Giannoccaro, V. Albino, M. Lezoche, A. Aubry, A. Giovannini, A. Buscicchio, **V. Leggieri** "Modelling framework for sustainable co-management of multi-purpose exhibition system: the "Fiera del Levante" case", Procedia Engineering 180, pp. 812-821, 2017 DOI: 10.1016/j.proeng.2017.04.242

CAPACITÀ E COMPETENZE PERSONALI

MADRELINGUA

ITALIANO

ALTRE LINGUE

	COMPRENSIONE		PARLATO		PRODUZIONE SCRITTA
	Ascolto	Lettura	Interazione	Produzione orale	
INGLESE	B2	B2	B2	B2	B2

CAPACITÀ E COMPETENZE INFORMATICHE

Ottima conoscenza:
- Sistema operativo Windows XP, 7, 8, 8.1, 10 e pacchetto Microsoft Office
- Software di modellazione e analisi strutturale (SAP2000, 3MURI, POR2000)
- Software GIS (QGis)
- Software di elaborazione 2D e 3D (AutoCAD, Artlantis)
- Software per la certificazione energetica (DOCET, MasterClima MC11300)
- Software contabilità lavori (PRIMUS)
- Software sicurezza cantieri (CERTUS)

Buona conoscenza:
- Linguaggio di programmazione MATLAB
- Software BIM (Autodesk Revit)
- Software di fotoritocco ed elaborazione video (Photoshop, Adobe Premiere Pro)

ULTERIORI INFORMAZIONI

Disponibilità a spostamenti su territorio nazionale e/o estero

PATENTE

B

Il sottoscritto dichiara di essere informato, ai sensi del d.lgs. n. 196/2003, che i dati personali raccolti saranno trattati anche con strumenti informatici esclusivamente nell'ambito del procedimento per il quale la presente dichiarazione viene resa.

Il dichiarante

Abstract

The seismic events of the last few years together with the short-term objectives imposed by European Union for the improvement of energy efficiency have brought to light the urgent need of assessing the actual performance levels to plan and realize suitable retrofitting interventions. This implies the necessity to perform large-scale surveys for a huge number of buildings for which it is not possible to use the procedures generally employed to assess single buildings, due to the detailed information required and the considerable computational burden. For this reasons, at large scale it is required the use of simplified procedures, easily implementable on the basis of limited information and able to provide results with acceptable reliability and accuracy, optimizing the cost and time connected to the process of realization of an inventory of building characteristics and subsequent implementation of the assessment procedures.

In this framework, the objective of the present research work is to provide an innovative approach for the assessment of the existing buildings in a context of uncertainty and incomplete information typical of the large scale analysis by means of a properly knowledge path to realize a suitable base of information finalized to theimplementation of several type of simplified assessment procedures with low computational effort.

Cover image: Foggia