# A consensus-based approach for Structural Resilience to Earthquakes using machine learning techniques

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# Abstract

Seismic hazards represent a constant threat for both the built environment but mainly for human lives. Past approaches to seismic engineering considered the building deformability as limited to the elastic behaviour. Following to the introduction of performance-based approaches a whole new methodology for seismic design and assessment was proposed, relying on the ability of a building to extend its deformability in the plastic domain. This links to the ability of the building to undergo large deformations but still withstand it and therefore safeguard human lives. This allowed to distinguish between transient and permanent deformations when undergoing dynamic (e.g., seismic) stresses. In parallel, a whole new discipline is flourishing, which sees traditional structural analysis methods coupled to Artificial Intelligence (AI) strategies.

In parallel, the emerging discipline of resilience has been widely implemented in the domain of disaster management and also in structural engineering. However, grounding on an extensive literature review, current approaches to disaster management at the building and district level exhibit a significant fragmentation in terms of strategies of objectives, highlighting the urge for a more holistic conceptualization. The proposed methodology therefore aims at addressing both the building and district levels, by the adoption of scale-specific methodologies suitable for the scale of analysis.

At the building level, an analytical three-stage methodology is proposed to enhance traditional investigation and structural optimization strategies by the utilization of object-oriented programming, evolutionary computing and deep learning techniques. This is validated throughout the application of the proposed methodology on a real building in Old Beichuan, which underwent seismically-triggered damages as a result of the 2008 Wenchuan Earthquake.

At the district scale, a so-called qualitative methodology is proposed to attain a resilience evaluation in face of geo-environmental hazards and specifically targeting the built environment. A Delphi expert consultation is adopted and a framework is presented.

To combine the two scales, a high-level strategy is ultimately proposed in order to interlace the building and district-scale simulations to make them organically interlinked. To this respect, a multi-dimensional mapping of the area of Old-Beichuan is presented to aid the identification of some key indicators of the district-level framework. The research has been conducted in the context of the REACH project, investigating the built environment’s resilience in face of seismically-triggered geo-environmental hazards in the context of the 2008 Wenchuan Earthquake in China.

Results show that an optimized performance-based approach would significantly enhance traditional analysis and investigation strategies, providing an approximate damage reduction of 25% with a cost increase of 20%. In addition, the utilization of deep learning techniques to replace traditional simulation engine proved to attain a result precision up to 98%, making it reliable to conduct investigation campaign in relation to specific building features when traditional methods fail due to the impossibility of either accessing the building or tracing pertinent documentation. It is therefore demonstrated how sometimes challenging regulatory frameworks is a necessary step to enhance the resilience of buildings in face of seismic hazards.

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# Nomenclature

| | |
|---|---|
| *AI* | Artificial Intelligence |
| *ANN* | Artificial Neural Network |
| *API* | Application Programming Interface |
| *BIM* | Building Information Modelling |
| *BSI* | British Standard Institution |
| *CAD* | Computer Aided Design |
| *DS* | Damage State |
| *EDP* | Engineering Demand Parameter |
| *FRP* | Fibre Reinforced Polymer |
| *GA* | Genetic Algorithm |
| *GUI* | Graphical User Interface |
| *IPCC* | Intergovernmental Panel on Climate Change |
| *IDR* | Inter-storey Drift Ratio |
| *IFC* | Industry Foundation Classes |
| *IQR* | Interquartile Range |
| *PCA* | Principal Component Analysis |
| *PSA* | Pseudo-spectral acceleration |
| *RC* | Reinforced Concrete |
| *UNDRR* | United Nations Office for Disaster Risk Reduction (former UNISDR) |

# Publications

## Journal publications

Cerè, G., Rezgui, Y., Zhao, W., Petri, I.: Using deep learning to enhance the resilience of buildings to seismic hazards. IEEE Transactions on Cybernetics, under review (2019).

Cerè, G., Rezgui, Y., Zhao, W.: Urban-scale framework for assessing the resilience of buildings informed by a delphi expert consultation. Int. J. Disaster Risk Reduct. 36, (2019).

Cerè, G., Rezgui, Y., Zhao, W.: Critical review of existing built environment resilience frameworks: Directions for future research. International Journal of Disaster Risk Reduction 25, 173–189 (2017).

## Conference proceedings

Cerè, G., Zhao, W., Rezgui, Y.: Structural behavior analysis and optimization, integrating MATLAB with Autodesk Robot. In: Mutis, I. and Hartmann, T. (eds.) 35th CIB W78 Conference: IT in Design, Construction, and Management. pp. 379–386. Springer, Chicago (USA) (2018).

Cerè, G., Zhao, W., Rezgui, Y.: Nurturing Virtual Collaborative Networks into Urban Resilience for Seismic Hazard Mitigation. In: 19th IFIP WG 5.5 Working Conference on Virtual Enterprises, Pro-Ve 2018. Cardiff, United Kingdom, (2018).

Cerè, G., Rezgui, Y., Zhao, W.:BIM tools for structural analysis in the Wenchuan Earthquake aftermath: Proceedings of the 12th ECPPM Conference: European Conference on Process Modelling. Copenhagen, Denmark 12th-14th (2018);

Cerè, G., Rezgui, Y., Zhao, W.: Displacement-based formulation of resilience: the case of a Reinforced Concrete building in Wenchuan': Poster presentation and abstract in the Proceedings of the 2018 Young Research Conference at the Institutions of Structural Engineers on April 10th, London (2018).

Cerè, G., Zhao, W., Rezgui, Y., Parker, R., Hales, T., MacGillvray, B.H., Gong, Y.: Multi-objective consideration of earthquake resilience in the built environment: The case of Wenchuan earthquake. In: 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC). IEEE, Madeira Island, Portugal (2017).

# 1. Introduction

Despite the significant technological and regulatory advances pertaining building design, seismically triggered damages to structures still account for a significant amount of casualties and financial losses. The present research proposes a methodology to enhance seismic resilience of new and existing reinforced concrete (RC) structures with a twofold potential for application at the building and district level. The current chapter will frame the research topic from a high-level perspective highlighting regulatory, societal and technological challenges. The ensuing steps encompass the definition of the core research problem resulting hence in the formulation of hypotheses and research questions. As a conclusion of this chapter, the main contribution of this research to the existing body of knowledge will be outlined.

## 1.1. Global view and research drivers

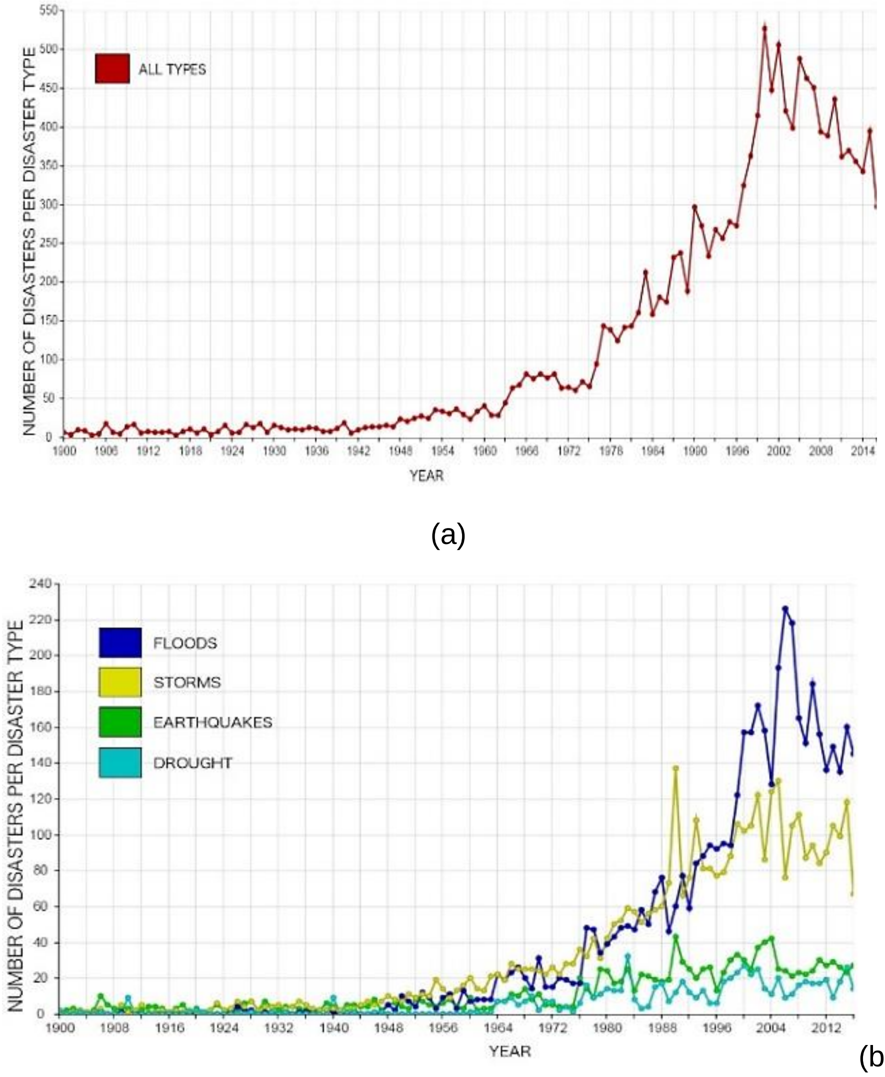
Seismic resilience has become an emerging topic in the last decades due to a high awareness in relation to natural hazards and their impact on the existing building stock. Consequently, the implementation of resilience in current preventive strategies is becoming increasingly important even though not yet officially implemented in regulatory frameworks. Nonetheless, the impact of geo-environmental hazards keeps undermining entire communities revealing an urge for more risk-based design strategies. Over the last few years, a great deal of world renowned institutions such as Munich Re and the UNDRR [1–3] have underlined the increased frequency in disaster occurrence (as displayed in Figure 1.1) and several efforts have been attempted to raise the awareness towards these matters. One of the most recent and relevant milestones has been the stipulation of the Paris Agreement at COP21 in 2015 with the main objective of averting temperature rise exceeding 2°C, to the pre-industrial levels, thus aiming at no more than 1.5°C in order to prevent serious impacts due to climate change [4]. Conversely to the past initiatives of the Kyoto Protocol and the Copenhagen agreement, 195 countries stipulated the Paris Agreement with the target of comparing mutual achievements every 5 years and to set better targets in favour of the environment.

Despite these initiatives at the local and global level, resilience is still not fully acknowledged outside the research community except from few situations [5, 6] where a more forward-looking approach is adopted. Overall, academia is perhaps the most receptive whereas in industry there is still substantial disagreement or at least lack of awareness of the long-run impact of a more resilient approach to design. The work by Bruneau et al. [7] paved the way to a new conceptualization of resilience in face of seismic hazards with the aim of transcending existing qualitative approaches and moving towards *quantifiable* resilience. Since then, resilience has become a buzzword and a great deal of research revolves around this topic and lately there has been a shift towards an interconnection with seismic performance-based approaches, in line with regulatory frameworks. However, as it will be demonstrated in this Thesis, the contribution provided by research often is not implemented by industry and the majority of the work remains stagnant.

This section therefore provides a high-level overview of the main drivers for this research taking into account both the external stressors and the reason for resilience demand, but also considering domains where a potential solution could be looked for.

### 1.1.1. Global impact of geo-environmental hazards

Over the past century and particularly in the last few decades, several countries worldwide experienced the ravaging consequences of different geo-environmental hazards. Figure 1.1 shows that undoubtedly the frequency of occurrence of geo-environmental hazards registered a consistent surge therefore leading to subsequent human, physical and financial losses. Notwithstanding the unrecoverable loss of human lives, physical disruptions to the existing built environment represent a threatening trend as shown in Figure 1.2. The report produced by UNISDR in 2015 [8] portraits an alarming negative trend of damages to existing building stock after the occurrence of geo-environmental hazards which is not decreasing in more recent years, despite significant regulatory and technologic advances. Figure 1.2 shows that despite the fluctuations in the registered damages to housing, education and healthcare facilities, there is an evident increase in damage linked to the above discussed intensified occurrence of geo-environmental hazards.

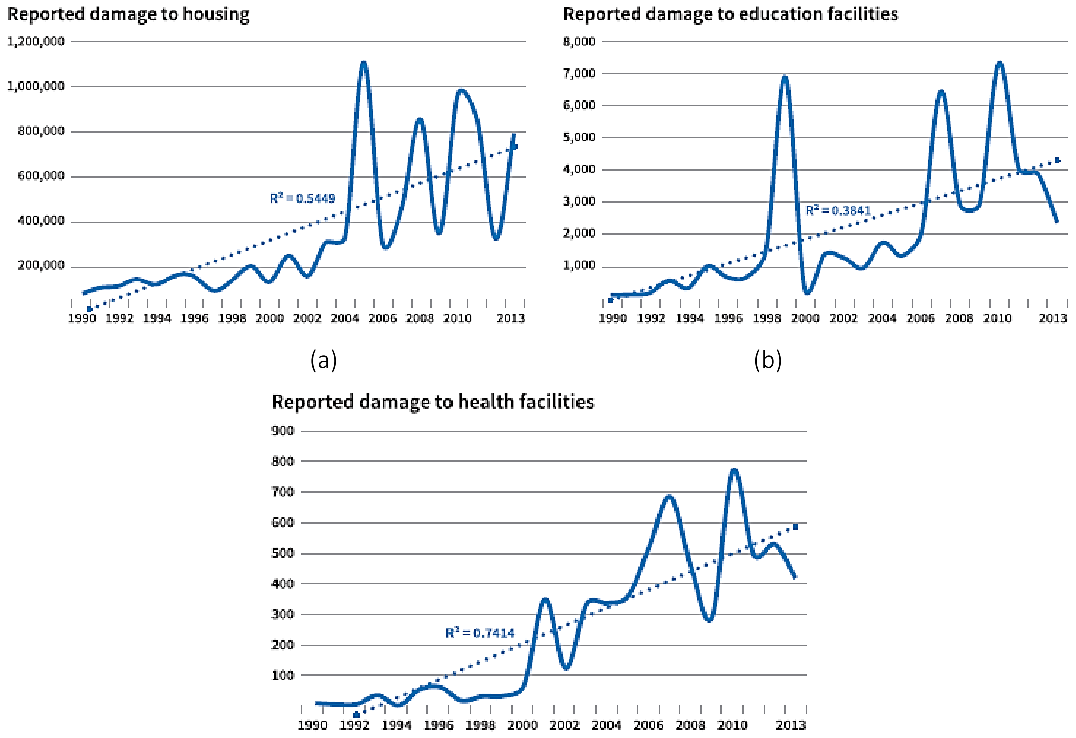


(a)

(b)

**Figure 1.1:** Disaster trends from 1900 to 2015. All types of disasters (a); Specific hazard categories (b) [http://www.emdat.be]

However, the impact of each hazards leads to diverse consequences based on a series of factors such as magnitude, site conditions, pre-hazard local vulnerabilities and disaster management in place. Figure 1.1 refers specifically to floods, storms, earthquakes and droughts and amongst them earthquakes are perhaps the only ones where a building-level resilience enhancement strategy would impact the most. With respect to floods, storms and droughts, their nature is such to need mitigation strategies at the urban, national or even global level. As a matter of fact, while earthquakes are not climate-dependent, the others are and their specific prevention is out of the scope of this research.



(a) (b)

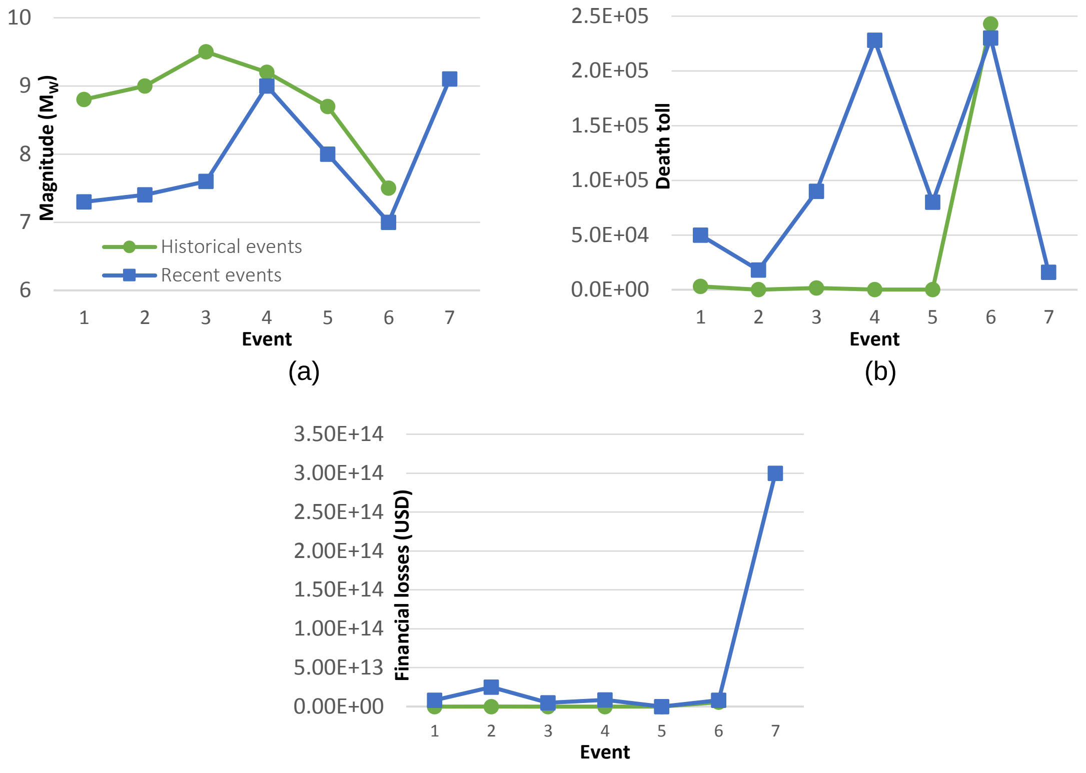
(c)

**Figure 1.2:** Amount of damaged buildings (y-axis) between 1990 and 2013 (x-axis) from extensive disasters in different categories: housing (a), education (b) and healthcare facilities (c) [source: [8]]

Earthquakes represent one of the most challenging hazards for engineers to forecast especially given the prevailing statistical nature of their forecasting. In line with previously presented data, Figure 1.3 shows that despite the significant technological advances and progresses in the structural engineering domain, the trend in terms of death toll and financial losses is still positive.

These data are significant especially given that the trend of events' magnitudes does not follow the same pattern, meaning that for a seismic event with a similar magnitude in the past, it is still possible to experience comparable losses. In detail it is worth observing how recent events caused a higher death toll and more financial losses than historical events, in contrast with one could expect in light of modern technological and construction advances.

It is pertinent to observe how historical events such as the Valdivia, exhibiting one the highest magnitudes in history, accounted for a recorded death toll of 1655 people [21] as opposed to the more recent Rudbar in 1990, where more than 40000 people lost their lives [10, 11].



(a) (b)

(c)

**Figure 1.3:** Comparison between historical (pre-1990) and recent (post-1990) seismic events in terms of (a) Richter magnitude $M_W$, (b) human, and (c) economic losses. The **historical** events (pre-1990) included in the review are enumerated as follows: 1-Valdivia, 1960 (Chile)[data source: USGS]; 2- Prince William Sound, 1964 (Alaska) [data source: USGS]; 3-Kamchatka, 1952 (Russia) [data source: USGS]; 4- Ecuador-Colombia, 1906 (Ecuador) [data source: USGS]; 5- Rat Islands, 1964 (Alaska) [data source: USGS]; 6-Tangshan, 1976 (China) [NGDC] [9]. The seismic events considered as **recent** consist in the following: 1- Rudbar, 1990 (Iran) ; 2-Izmut (also known as Kocaeli), 1990 (Turkey) [10, 11]; 3-Kashmir, 2005 (Pakistan) [12]; 4-Sumatra, 2004 (Indonesia) [13–15]; 5-Sichuan (Wenchuan), 2008 (China)[16, 17]; 6-Port-Au-Prince, 2010 (Haiti) [18, 19]; 7-Tohoku, 2011 (Japan) [20] [additional data source: USGS].

This highlights the relevance of factoring local conditions and targeting disaster management to the context as the vulnerabilities as highly site-specific. Some approaches are highlighting the relevance of considering singular contexts separately from others when dealing with hazards [22], however there is still a long way to go to attain a full awareness in this respect. In light of previous data and observations, the need for a more risk-aware approach to design becomes evident and to this respect, the ensuing sections will scale down to the merely structural engineering domain.

### 1.1.2. Advances in structural engineering analyses

Engineering cannot passively undergo technological advances, but these have to be factored into regulatory frameworks and their consideration is becoming increasingly important. A distinction has to be made however, in relation to software and augmented computational strategies, such as machine learning. The introduction of computers to support traditional engineering in the 20th Century paved the way to a consistent enhancement in simulation strategies, allowing designers to reduce calculation times while increasing the complexity of the structures [23]. Once discovered the inherent potential of software's computational power, engineers started to devise increasingly more complex structures with the 20th Century representing a milestone for structural design. With the advent of tall structures and skyscrapers engineering had to evolve accordingly by enhancing analysis strategies and technologic solutions, such as seismic dampers. Namely, former analysis methods not accounting for columns' axial deformation had to be revised due to the need of taking into account the wind action the consequent lateral displacement [23]. In their thorough analysis and in light of the significant advancements attained in the last century, Roësset and Yao [22] predicted current trends for structural engineering, namely highlighting:

- An increasing adoption of computational techniques to predict the location and extent of damage;
- The designer would be relieved by systematic simulation and calculation tasks, which would be assigned to a technician, while he/she could commit to the analysis of optimum solutions;
- A stronger influence of not directly structural factors would be embedded in design, especially regarding aesthetic, functionality and financial aspects;
- Higher implementation of performance monitoring systems on structures;
- The adoption of fuzzy logic, evolutionary computing and artificial neural networks would be integrated to traditional probabilistic strategies.

Clearly, given the exponentially fast technologic development experienced since the 20th century, engineers now are facing a similar challenge like the one proposed by the authors above. Whereas research keeps fostering the integration between traditional engineering and optimization-based strategies, structural engineers still show much reluctance to the implementation of such strategies into day to day practice.

### 1.1.3. Vulnerability of the built environment and its reduction

It is relevant to distinguish between resilience and its related concepts, such as vulnerability. Namely, vulnerability is defined as the condition that increases the susceptibility of al element in face of a specific hazard. Being the vulnerability case and scale-specific, its assessment varies for instance when addressing a building or an entire district [24]. Specifically regarding an urban district, the vulnerability does not consist in a linear function given the complex interplay across the variables featuring the system. Similarly to stress-strain steel curve [25], a system can be capable of absorbing elastically small entities of damage while if exceeding a certain threshold the level of loss can exacerbate despite the constant stress [26]. This is often the case for structures when the yielding condition is exceeded.

Vulnerability becomes particularly relevant in the domain of disaster resilience as it plays a key role in its prevention phase. In fact, given the definition of vulnerability provided above, it allows characterize the expected level of damage. However, this is the current stage attained by the majority of existing policies in face of hazards, where a forward-looking approach is not adopted and a static view on the system performance often prevails. The relatively recent regulatory transition from a prescriptive to a performance-based regulatory system played an important role in the promotion of risk and vulnerability-based initiatives.

Nonetheless several countries have been fostering initiatives to promote the seismic retrofit for buildings which do not comply with modern regulatory frameworks, and hence fostering their vulnerability reduction. The Federal Emergency Management Agency (FEMA) published a report containing the current initiatives in different areas of the US to deduct expenses for seismic retrofit from taxes [27]. FEMA has also supported technologic advancement to reduce the vulnerability of non-complying buildings, by establishing performance-enhancement guidelines for retrofitting. The California Department of Insurance can also guarantee loans to low-to-moderate income property owners [28] and earthquake insurance is also provided through the California Residential Earthquake Recovery Fund. Following to the 1994 Northridge earthquake an additional quasigovernmental institution was funded, the California Earthquake Authority, which guarantees additional insurance coverage to property owners in the occurrence of an earthquake. In Japan, following to the 1995 Kobe Earthquake, the Law Promotion for Seismic Retrofit was issued and performance-based design strategies were introduced in 1998 with a major revision of the building code standards [28]. Earthquake insurance in available based on a 3-level scale of seismic resistance for buildings in compliance with the Housing Quality Assurance Act law enforced in 2000 [28]. Italy saw the transition from a prescriptive to a performance-based regulatory system in 2003 [29] which was then reconfirmed in 2008 [30, 31]. The opportunity for property owners to deduct seismic retrofit expenses till a certain percentage was first introduced in the DPR 917/1986 and few updates occurred through the years with slight modifications increasing the percentage of tax relief in 2017 [32]. The initiative goes now under the label of “Sismabonus” and grounds on the concept of expected annual loss and the seismic classification of building performance established by the recently updated building regulatory framework [33]. This system revolves around the concept of “risk classes” which establishes a classification of decreasing seismic performance from A+ to G. As per definition of risk [34], its formulation results from the combination of exposure, hazard and vulnerability.

## 1.2. Current challenges for resilience and structural engineering

The previous section focused on the most critical aspects in terms of building management in face of seismic hazards and the rise of artificial intelligence in structural engineering. A consistent disparity in terms of will to integrate new techniques was highlighted between research and industry, with the latter being highly reluctant. This section will explore further current challenges in terms of resilience management and risk-based policies but it will also outline some shortcomings in the structural engineering domain.

### 1.2.1. The need for innovation in structural engineering

Despite its apparent domain-specific nature, structural engineering is renowned to be highly interconnected to the other related domains, namely architecture and the emerging Building Information Modelling (BIM) techniques [35, 36]. As presented in the previous section, the rise of computing power resulted in extremely benefitting consequences for engineers given the opportunity to embed additional complexity to the design. The advent of software like Graphisoft Archicad and Autodesk Revit paved the way to a new and holistic modelling strategy of building, stemming from a collaborative conception of the design process able to involve all the aspects (e.g., structure, architecture, installations) at once. The collaborative trend in design became urgent also since the development of web-based communication systems and the enlarged geographical distribution of the project participants [37].

Another driver towards this trend stems from the call for the increasing complexity of buildings to be credited by SEI [38]. The Structural Engineering Institute highlights the recent conservative attitude of structural engineering which consistently relies on the robust regulatory framework that it has established. On one side, this is reassuring from a professional whose great responsibility is to ensure life safeguard in face of major hazards. On a different note, with the increasingly constraints imposed by regulatory frameworks and costs, the space for engineering judgment and design choices is few. The SEI in 2013 to this regards stated: "*We must manage this risk better to enter a more creative and innovative future. We must find a way to curb our impulse to put our every technical thought into a code or specification. We must find* *a way to return engineering judgment to the top of the list of reasons why structural engineers are valuable and why creative people aspire to be structural engineers*."

In order to pursue innovation and integration in structural engineering the SEI calls for an even stronger integration between the disciplines, adopting a holistic understanding and avoiding the attitude of considering "*construction, economics, architecture, and public policy as 'other disciplines'*" [38]. There is also a strong urge to go beyond building regulations prescriptions in order to re-gain critical thinking to develop innovative solutions and not relying passively on building codes.

### 1.2.2. Risk-informed disaster management

Despite the considerable effort placed in devising practical resilience tools such as the ones proposed by Da Silva [6], Field [5] and Cimellaro et al. [39], the effective integrations of those into practice is still far from being the standard. Existing research highlights in fact that regulatory bodies do not explicitly factor disaster-management policies and resilience in their approaches [40]. It is however pertinent to mention that a first step towards a formalization of resilience within standard building codes is being attempted by Bristish Standard Institute (BSI) in the United Kingdom [5]. Research evidence also highlights a worrying disconnection between stakeholders, resilience policies, building regulations and private owners. Namely, clear obstacles exists to a concrete implementation of resilience in practical disaster prevention and management, according to Bruneau and Reinhorn [41]:

- Absence of resilience requirements within building codes specifications and apparent lack of implementation in the near future;
- Misinterpretation of resilience not as a pre-established standard requirement but as a post-disaster attained condition;
- Lack of awareness from private buildings' owners with respect to why and what is addressed when applying resilience enhancement and prevention strategies;
- Disconnection between objectives pursued at the building and community level in terms of resilience planning and application.

In harmony with the directions proposed by Bruneau and Reinhorn, former research by Carpenter et al. [42] already highlighted the need to clearly identify and target a specific aspect of resilience while proposing a new strategy for its quantification/qualification. Resilience has attracted considerable interest both in the academic and industrial environments especially over the last decades and the research work addressing it has registered a surge particularly in the last 15 years [41]. Nonetheless, the engineering domain demands for resilience strategies that would firstly lead to a concrete quantifiable entity and propose a method targeting a precise objective for resilience-enhancement and assessment [41]. Given the multi-faceted nature of resilience, strategies for disaster management and prevention involving resilience have to be interdisciplinary [41] also entailing a deep risk-awareness [43].

## 1.3. Problem statement

The topic of resilience is not novel to the building engineering domain, both from a disaster-management perspective but also encompassing structural design. However, current and past approaches rely on static methodologies which do not fully exploit the potential of modern technologic development, such as the ones provided by AItechniques. Current research proves that the technologic advances did not happen seamlessly in construction industry, and an evident example is the integration of Building Information Modelling (BIM) strategies. On the other side, the disconnection existing amongst district-scale analyses and building-level performance assessments often results in scattered approaches with limited application. Therefore, the integration of resilience on one side and computational strategies on the other, leads to a holistic and scalable consideration of the building performance with the simultaneous generation of a vast series of option factoring costs and vulnerability thanks to the adoption of AI ensembles.

## 1.4. Context of the research

The proposed research has been developed in the context of the REACH project, which encompassed the investigation of resilience in the aftermath of the 2008 Wenchuan Earthquake in China [44]. This project also draws on a multi-disciplinary and international collaboration across the United Kingdom and China, namely between the Schools of Engineering, Geology and Social Sciences in Cardiff and the Chengdu University of Technology.

The acronym REACH derives in fact from “Resilience to EArthquake in CHina” and aims at investigating the impact of seismically-triggered geo-environmental hazards in the aftermath of the 2008 Wenchuan Earthquake in China, specifically addressing the built environment. The outcomes of the research should functional to provide lessons learnt from past events and therefore develop a methodology able to tackle seismic resilience in a proactive manner.

The role of the researcher was in this context to conduct site investigations and 3D laser scanning across the Wenchuan province in China functional to the development of reliable building models. The latter were then adopted to investigate the resilience of buildings in face of seismic hazards and therefore create an opportunity to develop a strategy for resilience enhancement in face of future catastrophes.

## 1.5. Research aims and objectives

Grounding on the arguments delineated above, the overarching hypotheses and subsequent research questions are formulated in the current section. Namely, this research intends to propose a more technology-aware and risk-based methodology for investigation, assessment and performance-enhancement of reinforced concrete (RC) structures in face of seismic hazards through a three-step methodology. This is attained by dint of the consideration of key building performance indicators and the manipulation of relevant variables in order to fully exploit the potential of the integration between Artificial Intelligence techniques and structural design.

The thesis addresses the following gap:

"*Existing building regulations do not confer optimal earthquake resilience to our buildings. These regulations focus on buildings and do not address resilience at a wider district level*."

In pursuit of a knowledge contribution and with the aim of evaluating the above hypothesis, the research questions that this work will try to answer consist in the following:

1. Can a disaster management framework be developed to address buildings' resilience at the district level with a holistic consideration of related factors?
2. How can structural design parameters be inferred to accurately characterise and model a seismically compromised building in case of limited access to data and lack of supporting documentation?
3. Can the governing variables most sensitive to the structural integrity of a building be inferred taking into account a wide range of considerations, including local environmental and geotechnical conditions?
4. Can these sensitive variables inform the development of less computationally demanding structural analysis models with a view to optimize the structural design of a building?

Each research question will be further discussed and analysed in each pertinent Chapter and specifically Chapter 2 will delineate a thorough literature review to establish a solid ground for the ensuing research work.

## 1.6. Thesis outline

This Chapter outlined the wider background functional to contextualize and justify the presented research. Chapter 2 will instead delineate a literature review addressing a more focused view on the topics highlighted in this Chapter and expanding it according to relevant emerging topics. Namely, resilience will be defined adopting a top-down approach and scaling down to qualitative and quantitative approaches, with a view on existing resilience frameworks. At the same time, applications of AI techniques in structural engineering will be extensively analysed as well as the underpinning theoretical and methodological processes for the selected algorithms. A more focused analysis on modelling strategies and software for existing buildings, as well as algorithms adopted to digitally represent structural features will be provided and explored.

Chapter 3 will focus instead on the research methodology overview, providing the overarching theoretical justifications and the ensuing technical approach. The methodology will also include an overview of the project adopted for the validation of the current research work, as well as basic calculations for pseudo-acceleration spectra relatively to the 2008 Wenchuan Earthquake and preliminaries for the more in-depth work presented in the ensuing Chapters. The presented methodology will be distinguished into district and building-level in order to provide a clearer picture of the work.

The district-level approach is encompassed in Chapter 4, where the resilience management framework is developed and a comprehensive overview from its initial conceptualization to results is provided. Chapter 5 will instead tackle the integration between augmented machine learning techniques and structural analysis in order to enhance investigation, optimization and damage forecasting strategies. This will be further validated on a case-study building with additional considerations on the compliance with regulatory frameworks and how to enhance seismic resilience.

Chapter 6 will instead combine the previous two approaches into a single framework for a scalable and adaptable resilience management strategy. Further discussion and concluding remarks will be provided in Chapter 7 with a highlight of the attained contributions. Research questions and hypothesis will be discussed in light of the results and consequently relevant limitations and future work directions will be outlined.

## 1.7. Contribution

The main contributions to the body of knowledge can be preliminarily summarised as follows:

- **At the district-level**: a comprehensive and holistic approach to disaster resilience management is provided specifically targeting the built environment. The methodology factors local environmental conditions and hazard-specific variables as well technical-organizational features to develop a risk-aware framework to assess the seismic (but also more generically geo-environmental) resilience of an urban system.
- **At the building level**: a framework to investigate, optimize and predict damage to structure is proposed adopting a performance-based approach. The overarching methodology exploits the potential of augmented machine learning techniques and evolutionary computing to enhance traditional structural analysis strategies by the proposition of a 3-stage approach featured by increasing abstraction and complexity of the deployed ensembles. The approach is scalable and flexible given the full potential for integration of both linear and nonlinear analysis techniques for structural behaviour assessment.
- **Combining district and building levels** a scalable approach can be pursued to inform resilience strategies for enhancement or as-built assessment, factoring in the urban context also building-specific features, respecting the scale-specific level of detail in terms of involved variables hence not penalizing the quality of the results.

In addition to the above, the contributions of this research can further be classified into the potential for application in the following circumstances:

- **Pre-disaster condition**: providing a tool to optimize the design of RC structures in face of seismic hazards. This is also achieved at the district scale by identifying the weakest resilience criteria and consequently devising a strategy to strengthen the resilience capacity by targeting bespoke disaster management strategies. **Post-disaster condition:** The potential of the methodology can in this case be exploited by auditing the building performance in the aftermath of the disaster and investigating the optimum retrofit strategy to enhance future resilience capacity. However, the integration of structural monitoring health systems provides the opportunity of achieving an almost real-time resilience performance representation of the building or district.

# 2. Literature review

The current chapter will initially explore the concept of resilience adopting a top down approach and therefore moving from the wider context to the research topic where its application is intended. Following to that, the focus is moved on the categorization and further analysis of different approaches and applications of resilience in the engineering and disaster-management domains. Section 2.4 will target instead computational techniques in the domain of structural engineering. Grounding on the provided overview and considerations, the end of the section will outline the research gaps as well as present the research questions. The present work partially builds upon the research published by Cerè et al. but it has been enhanced and expanded in this context.

## 2.1. The development of resilience

Despite its relatively recent versatile application across a wide range of fields, the concept of resilience can trace its roots back to the Ancient Greek literature within the noteworthy work of authors such as Seneca the Elder, Pliny the Elder, Ovid, Cicero and Livy [45]. More recent research locates the first uses of the term in the Lucretius' “Nature of Things” dating back to the first century B.C. [46]. It is however agreed that in more recent times the concept of resilience has been borrowed to characterize the ability of a human being to recover from disruption, becoming of particular use in the psychiatric domain. Namely, this is the case of the work by Norman Gamezy, Emmy Werner and Ruth Smith [47–49]. From an etymological perspective, the term resilience originates from the Latin verb *resilīre* and meaning “to jump back” [14, 45].

Resilience is also familiar to engineering as it identifies in the steel tensile test diagram the energy absorptive capacity during the elastic phase of a deformation process and the subsequent capacity of recovering when unloaded [47, 50]. Being resilience the area underneath the elastic portion of the diagram, its formulation is therefore the integral having as extremes the bound values of the considered curve [50].

Nonetheless, existing research agrees in identifying Holling as the father of more recent conceptualizations of resilience. His research encompasses mainly ecological systems [51] but the broader definition of resilience can be extended to any system. In fact, resilience is generally identified as the capacity of a system to withstand an external disturbance and proactively recover towards a new stable performance [51]. Latest approaches [52] contrast this view and define resilience as a “neutral” inherent property of a system, not necessarily positive but that can also result in undesired consequences if the adaptability of the system does not suffice the system's ability to cope with the hazard.

In the last decade an evident shift has been registered in the way resilience is conceptualized, with an increasing trend in problematizing the rebound to a pre-disaster condition as a desirable recovery standard [43, 53]. As opposed to this view, new approaches tend to rely on adaptation rather to an "elastic" rebound and therefore it is expected that a system would recover attaining a new equilibrium condition which is not necessarily equivalent to the pre-disaster one. Having said that and recalling the association with the steel stress-strain diagram, whereas the first view can be identified as "elastic". Resilience definitions relying on the adaptive capacity of a system could be conversely identified as "ductile", given the material (or system, in the case of resilience) capacity of absorbing significant stresses but still being able to undergo large deformations. Chandler and Coaffee, adopting more biology-based association but yet with a similar significance, define the "elastic" approaches as *homeostatic* and the others as *autopoietic* [54]. An additional form of resilience is identified in the present, hence differently from the past-focused (i.e., homeostatic) and adaptive one (i.e., autopoietic) [54]. This new resilience conceptualization should aid decision making processes in the short terms.

An evolutionary approach to resilience would find a concrete application in the engineering domain for instance when dealing with seismic events. It is in fact not recommended rebuilding with the intent of replicating a situation which proved to be unsuitable to withstand a certain level of stress [55]. Buildings should in fact be rebuilt with the aim of enhancing the performance and in accordance to the most updated regulatory frameworks. A pertinent example is the 2010 Haiti earthquake that hit Port Au Prince [56], where the adoption of a conservative approach trying to replicate a pre-disaster situation led to the failure of structures and infrastructures. Similarly, when dealing with historical buildings, the so called "conservative restoration" principles do not allow to restore mimicking the original condition, but the interventions have to be clearly distinguishable [57].

In order to filter the most relevant approaches of resilience in relation to engineering and disaster-management perspectives, the works germane to this research were categorized according to their pertinence to a specific domain. Namely, four clusters were identified as follows:

- Ecological: including approaches addressing socio-ecological systems (SES);
- Socio-technical: relating to strategies directed at enhancing resilience at the urban-level;

- Built-environment: referring to those publications which apply resilience to both buildings and infrastructures;
- Networks: dealing with interconnected systems in the broadest sense (e.g., telecommunications and road networks) either at the urban or regional scale.

Table 2.1 provides the breakdown of the most relevant approaches and the disruption that it is addressed in the specific research. The works are also categorized according to the adopted approach, whether it is quantitative or qualitative and these will be further examined in the ensuing sections.

**Table 2.1:** Categorization of relevant approaches dealing with resilience (G = General disruptions, F = Floods, E= Earthquakes, RF = Rock Falls, SMS = Slow-moving slides, RFS = Rapid Flow-type slides)

| Author(s) | Ecological | Socio-Technical | Built Environment | Networks | Hazard |  |  |  |  |  | Quantitative | Qualitative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | G | F | E | RF | SMS | RFS |  |  |
| Bruneau et al. 2003 [7] | x |  | x | x |  |  | x |  |  |  |  | x |
| Chang et al. 2004 [58] |  |  | x |  |  |  | x |  |  |  | x |  |
| Kircher et al. 2006 [59] |  |  | x |  |  | x | x | x | x | x | x |  |
| Cimellaro et al. 2006 [60] |  | x | x |  |  |  | x |  |  |  | x |  |
| Bruneau and Reinhorn 2007 [61] |  | x | x |  |  |  | x |  |  |  | x |  |
| Cimellaro et al. 2008 [39] |  | x | x |  |  |  | x |  |  |  | x |  |
| Cutter et al. 2008 [62] | x | x |  |  | x |  |  |  |  |  |  | x |
| Kaynia et al. 2008 [63] |  |  | x |  |  |  |  |  | x |  | x |  |
| McDaniels et al. 2008 [64] |  | x |  | x |  |  |  | x |  |  |  | x |
| Cimellaro et al. 2009 [47] |  | x | x |  |  |  | x |  |  |  | x | x |
| Cimellaro et al. 2010 [65] |  | x | x |  |  |  | x |  |  |  | x | x |
| Cimellaro et al. 2010 [66] |  |  | x |  |  |  | x |  |  |  | x |  |
| Folke et al. 2010 [67] |  | x |  | x |  | x |  |  |  |  |  | x |
| Miles and Chang 2011 [68] |  | x | x |  | x | x | x | x | x | x | x | x |
| McAllister 2011 [69] |  | x | x |  |  |  | x |  |  |  |  | x |
| Henry and Emmanuel Ramirez-Marquez [70] |  | x |  | x | x |  |  |  |  |  | x |  |
| Ouyang et al. 2012 [71] |  |  | x | x | x | x | x | x | x | x | x |  |
| Zobel and Khansa 2013 [72] |  |  |  | x | x | x | x | x | x | x | x |  |
| Francis and Bekera 2014 [73] |  |  | x | x | x | x | x | x | x | x | x |  |
| Mavrouli et al. 2014 [74] |  |  | x |  |  |  |  | x | x | x | x |  |
| Alshehri et al. 2015 [75] |  | x |  |  | x |  |  |  |  |  |  | x |

| Author(s) | Ecological | Socio-Technical | Built Environment | Networks | Hazard | | | | | | Quantitative | Qualitative |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | G | F | E | RF | SMS | RFS | | |
| Barberis et al. 2015 [76] | | | x | | | | x | | | | x | |
| Franchin and Cavalieri 2015 [77] | | | x | | | | x | | | | x | |
| Uzielli et al. 2015 [78] | | | x | | | | | | x | | x | |
| UNDRR 2016 [79] | | x | x | | x | | | | | | | x |
| Vona et al. 2016 [80] | | | x | | | | x | | | | | x |
| Field et al. 2016 [5] | | x | x | | x | x | x | x | x | x | x | |
| Labaka et al. 2016 [81] | | x | x | x | x | x | x | x | x | x | | x |
| Mahsuli [82] | | | x | | | | x | | | | | x |
| Karamouz and Zahmatkesh 2017 [83] | | x | x | | | x | | | | | x | |

For most of the analysed frameworks, resilience is usually deconstructed into different phases and generally [84] they are defined as disaster prevention, propagation and recovery. Namely, disaster prevention coincides with the timeline that precedes the hazard occurrence, while the propagation entails the whole duration of the disaster. Conversely, from the immediate aftermath onward, reconstruction can take place. It is however observed that in the aftermath of a disaster it is pertinent to include the assessment stage [71], and not only reconstruction, as the first is key to then suitably tailor the latter.

This section provided a theoretical overview of resilience, highlighting its origin and applications in the disaster management and engineering domains. The following sections will aim at identifying any recurrent themes or applications for resilience amongst the research presented above.

## 2.2. Qualitative resilience approaches (District-level resilience)

This section encompasses the frameworks targeting a wider context for resilience management and enhancement, such as urban, regional or even national level. Differently from the quantitative frameworks which mainly address the building-scale, the ones featured herein include buildings and infrastructure not as the object of resilience evaluation, but as one of the concurrent characteristics of the urban system. The analysed frameworks are further categorized into two groups depending on their academic or institutional derivation. The first group includes those frameworks devised by relevant institutions at the national or global level promoting resilience and fostering its implementation in common practice for disaster management and climate change. Complimentarily, the second category narrows down the focus to building-scale methodologies which are devised to assess the resiliency of a building through its structural performance.

### 2.2.1. Institutional frameworks

This category embeds those frameworks which target resilience as a by-product of measures adopted to address climate change, but it also features approaches addressing resilience directly although on a wide geographical scale of analysis. Nonetheless, the consideration of the first ones is not meant to deviate the focus on the research but to strengthen the correlation amongst climate change and increase of geo-environmental hazards occurrence.

A representative example was the Hyogo Framework for Action devised in 2005 during the World Conference of Disaster Reduction which constituted a key milestone for the ensuing disaster mitigation strategies [85]. The positivist stance driving this strategy led to address the enhancement of resilience instead of the reduction of risk. This thread was maintained also regarding the “Make My City Resilient” campaign promoted by the United Nations Office for Disaster Risk Reduction (UNDRR) which advocates for a holistic planning of resilience fostering its inclusion in disaster management [1, 86]. The UNDRR strategy to attain resilience includes a list of 10 “Essentials”:

1. Organize for Disaster resilience;
2. Identify, understand and use current and future risk scenarios;
3. Strengthen financial capacity for resilience;
4. Pursue resilient urban development and design;
5. Safeguard natural buffers to enhance ecosystem protective functions;
6. Strengthen institutional capacity for resilience;
7. Understand and strengthen societal capacity for resilience;
8. Increase infrastructure resilience;
9. Ensure effective disaster response;
10. Expedite recovery and build back better.

The essential attributes as defined by UNDRR clearly include all the different phases of resilience as described in Section 2.1, namely disaster preparedness, robustness and recovery. In the context of this initiative the MOSE barriers to protect Venice lagoon from the rising tide owned Venice the title of “Model for resilience” [87, 88]. These barriers are designed to rest underwater during normal operational conditions. However, air is injected with consequent expulsion of water and the resulting lifting on the panels when the flood risk is identified. The Oosterschelde and Maeslantkering barriers in Netherlands are other noteworthy examples of flooding management and resilience enhancement interventions. United Kingdom is another country which fights against tidal surges and to tackle the consequences of their occurrence, London has equipped the Thames with moving barriers which would serve this purpose [89]. Earthquake resilience represents another major challenge and to this regard Vona et al. [80] advocate for a more city-level resilience planning in Italy, to contrast the lack of emergency planning in face of these hazards. However, addressing just one scale would result in neglecting the big picture and losing the focus on how the different city-level resilience approaches are interlacing with each other. An emerging risk while devising this large-scale interventions is for resilience to be considered as a "by-product" instead of representing the main objective in the long-run [46]. A successful example of resilience achievement in face of geo-environmental hazards at country-level is embodied by Cuba. Pertinent research [90] highlights that the success of the Cuban context stems on a series of strategies that coincide also with the "Essentials" devised by UNDRR.

The United Nation Framework Convention on Climate Change (UNFCCC) reaffirmed the need to mitigate the effects of climate change by strategizing how to not exceed the raise of 2°C for the global temperature sine pre-industrial levels [91]. This was formalised in the Paris Agreement which calls for a stronger mutual support across developed and developing countries to build a sustainable future, fostering transparency, preservation of reservoirs and collaboration for the pursuit of long-term goals.

A noteworthy example of urban-scale resilience framework consists in PEOPLES [92], devised by Renschler et al. on behalf of the National Institute for Standard and Technology (NIST). This framework proposes a performance-based seismic engineering assessment of buildings adopting a multi-layer resilience conceptualization [93]. The domains involved to assess resilience range from social-organizational aspects to environmental, including also infrastructural and financial dimensions. The framework will be further explored in its components in section 3. Resilience is herein featured by the "four Rs", namely Robustness, Redundancy, Recoverability and Resourcefulness devised in previous research by Bruneau et al. [7]. A distinguishing feature of the PEOPLES framework consists in the ability to connect the wide-scale resilience (i.e., urban, district-level) to the building one. This is attained assessing the actual/predicted performance of a structure at the building level and then, by means of network theory, factoring it into the global model. However, the overall methodology entails a considerable amount of computational capacity and elaborations, in addition to the fact that optimization strategies are not included.

The Rockfeller Foundation and Arup proposed instead a resiliency framework intended to measure the relative resilience over time in order to be applicable in a multiplicity of contexts with a specific focus on humanitarian aid [6]. Resilience is identified through a series or properties that respect to the ones proposed by Bruneau et al. [7] neglect Recoverability but feature resilience as Reflective, Integrated, Inclusive and Flexible. Conversely to the previous framework, the City Resilience Index is specifically devised to address wide contexts, namely at the urban scale. On one side, this allows a specific target to the approach but it adds a significant downside, which is represented by a rather limited scalability. This is also confirmed by current trends in demand for resilience approaches where a scalable strategy leads to a more flexible applicability in concrete applications.

Similarly to the City Resilience Index [6], Buro Happold in conjunction with the BRE institution and the Worshipful Company of Constructors advanced their own resilience assessment framework [5]. As opposed to the City Resilience Index, this framework clearly state the measuring strategy adopted to quantify resilience which employs the same concept of performance-based verifications in structural engineering. The ratio between the capacity and the demand provides the resilience rating and then potential for further improvements is calculated by subtracting the capacity to the demand. Although this framework adopts a multi-hazard and risk-based approach, it is featured by the same limitation of the City Resilience Index being constrained to one scale of analysis.

### 2.2.2. Research-based frameworks

Although the work initiated by Bruneau led research team over the years translated into a metric, as it will be outlined in the following section, his approach commenced with a rather qualitative resilience conceptualization. The seminal work carried out by Bruneau et al. [7] lied the foundations for ensuing works aimed at assessing and enhancing the resilience of healthcare facilities and infrastructures in seismic conditions, especially in conjunction with Cimellaro’s rsearch [60, 66]. However, the initial framework for resilience proposed by Bruneau in 2003 [7] focusses on communities in their whole. Resilience is featured by four main dimensions constituting the TOSE model: (i) Technical, (ii), Organizational, (iii) Social, and (iv) Economical. As alluded to in the previous section, Bruneau et al. also identified four properties for resilience, the so called “four Rs”, which are represented by Robustness, Redundancy, Resourcefulness and Recoverability. This research has constituted the main thread for a great deal of research work, culminating in the PEOPLES framework presented in the previous section.

The enhancement of community resilience is also tackled by Alshehri et al. [94] by means of a Delphi-based expert consultation to validate the criteria determining resilience in face of geo-environmental hazards. As mentioned at the beginning of the section and given the nature of community-based resilience frameworks, a significant influence on resilience is attributed to the social aspects.  This translates for instance into how inhabitants perception of the community and authorities, education, use of social networks and personal beliefs. Comparing for instance the City Resilience Index devised by Arup and the Rockfeller Foundation with the one devised by Alshehri some relevant differences can be spotted in relation to the infrastructural criteria. With respect to the Arup's "Infrastructures & Ecosystems" section, corresponding to "Physical and environmental" in Alsheri's framework, it is possible to acknowledge how redundancy of infrastructural network is involved in both approaches, as well as the exposure of existing buildings and infrastructures. The City Resilience Index however tends to group many features under categories that become difficult to measure, such as the criterion "Effectively managed protective ecosystems".

An essential feature when dealing with environmental hazards consists in the lessons learnt following to disasters occurred previously, and this is not clearly stated in the physical infrastructures sections unless implicitly considered in the enforcement of the regulatory systems. However, building regulations are not always updated after the occurrence of a disaster if governmental institutions are not sufficiently risk-aware. Another example can be the "management of waste created by natural hazards" which is clearly stated in Alshehri approach while in the City Resilience Index is not explicitly listed. It is fact mentioned the management of "solid waste" [6, 95], but mainly with respect to waste produced on a daily basis, whereas it is of primary importance to take into account the impact of debris in the aftermath of a disaster, as the example of Old Beichuan shows. After the 2008 Wenchuan Earthquake, the city was in fact totally isolated because of the debris, to the point that the death toll increased significantly as a consequence of the impossibility for emergency rescue services to access the site.

The infrastructural dimension is perhaps the only one that consistently differs when comparing the two frameworks, but on the whole the indicators in the City Resilience Index appears sometimes not self-explanatory and clearly interpretable. Overall, Alsheri's framework appears to be advantageous given the nature of the criteria, which are comprehensive enough to be applicable at the community level but at the same time specific in what they address making them easily measurable and quantifiable. On a different note, the City Resilience Index is generic enough to cover a multiplicity of criteria, but this entails the difficulty of readability and interpretation of meaning of some the indicators.

Ultimately, a research encompassing resilience cannot overlook the work on small states and islands accomplished by Briguglio. Small states are featured by economic openness and trade, especially in terms of food, water and fuel imports [96]. However, the need of relying on external imports constitute an hazardous vulnerability in the occurrence of stressors that might affect the trade [96]. Even though Briguglio's work mainly encompasses economic resilience, the seminal contribution provided for the Intergovernmental Panel for Climate Change (IPCC) in 2003 highlighted a series of disaster indicators for resilience which are mirrored in the most recent frameworks previously analysed in this chapter. It is pertinent to mention that in the report a series of "orienting questions" are also posed to guide the assessor through the evaluation, and what stands out is the foreseeing approach in proposing a tangible, objective-oriented and measurable resilience strategy structured into a series of clear, simple and self-explanatory indicators. Even though focussing clearly on economic resilience, the approach is holistic and inclusive of a series of criteria that would easily make it suitable for a multi-hazard approach.

At the district scale, an emerging research thread adopts a network-based approach to deal with complex interdependencies of the urban system. As emphasized by existing research [97], urban systems consist in highly interconnected networks featured by a potential intrinsic fragility resulting from cascade failure and chain of events when resilience is not addressed. However, despite the successful multi-disciplinary applications of complex networks strategies [98] ranging from biology to structural engineering, for the purpose of this research such approach would be unsuitable. Namely, district-level resilience and disaster management are tightly related to decision-making strategies and human-related factors which are hardly quantifiable. As a consequence, the adoption of a highly analytical strategy would not suit the purpose of this analysis, where a significant role at the district scale is played by processes and strategies which cannot be measure in a univocal manner.

In light of the above, it can be observed that research-based work highlights a more focussed understanding of resilience and in diversified realities (e.g., communities, urban or isolated contexts), whereas the institutional strategies tend to approach the problem from a rather top-down perspective but losing of scalability and interpretability [5, 6]. On the contrary, approaches such as the UNDRR [99] and PEOPLES [92] manage to place in an intermediate level where enough specificity is given to address diversified scales of analyses.

### 2.2.3. Summary

The literature presented in this section evidences a rich body of knowledge in relation to qualitative approaches for resilience assessment. Namely, these are categorized in research-based frameworks and approaches developed outside academic environments (i.e., institutional). Research approaches perhaps manage to capture more accurately the diversity of environmental and urban contexts, providing a range of resilience approaches that highlight its scalability. Institutional-based frameworks tend on the contrary to be more generic and addressing resilience in face of a variety of hazards, hence sometimes losing of applicability due to the failure in capturing hazard-specific features.

The review devised until this point allowed to reveal a need for resilience-management approaches capable of targeting a specific objective in face of a determinate hazard, however this is mostly attained by research-based approaches. This is due perhaps to the fact that some of these frameworks originate from building-scale methodologies which have been adapted and generalized to district-scales, hence preserving the focussed approaches that features micro-level strategies. Furthermore, whereas institutional frameworks tend to adopt a community-scale approach, research strategies appear to better capture the technical aspects of resilience.

The scope of section 2.2 was to analyse existing district-level resilience frameworks in order to investigate which are the governing features that are currently factored into a disaster management approach. This would inform the development of the proposed framework allowing to identify which gaps are currently not addressed. Namely, the cross-comparison of both research and institutional frameworks provides a good overview of how disaster management resilience frameworks are generally structured into a series of governing criteria which are further clustered into pertinent categories (e.g., environmental, infrastructural, governmental). From a technical perspective, research-based frameworks perhaps exhibit a deeper understanding of the micro-level technical aspects, whereas institutional frameworks are able to successfully factor management strategies. Both approaches (i.e., research and institutional) adopt however a similar score-based methodology for the final assessment of resilience. As a result, the proposed research would benefit from a similar structure, in order to break down the representing features of buildings' resilience and enabling their quantification.

With respect to the techniques adopted for the creation and validation of the proposed frameworks, whereas some of them adopted focus groups and discussions

[5], other research opted for Delphi-based expert consultations [94]. For the scope of this research it is maintained that a Delphi-based consultation would benefit the most because of the enriching opportunity of involving a global and multi-disciplinary research and industrial community of experts. From a merely research-related standpoint, a Delphi consultation would perhaps encourage the participants to provide their contribution given the opportunity of answering the questionnaire whenever it is most convenient during a relatively long timeline of usually a month. Moreover, the benefit of adopting a Delphi technique ensures the total anonymity of the experts. Grounding on the above reasons it is believed that a Delphi-based consultation would strongly benefit the current research approach with respect to the qualitative resilience framework [43, 100].

## 2.3. Quantitative resilience approaches (Building-level resilience)

Over the years there has been an emerging need to define a numerical metric for resilience although its loose definition regardless of the domain is associated with the inherent system's capacity of withstanding a stress and bounce back to a suitable performance level [83]. As visible in Figure 2.1, an initial broad separation is identified with respect to multi and single-hazard resilience approaches [43]. However, given the impossibility of targeting resilience towards a specific stressor and in relation to a defined elements, multi-hazard approaches alone cannot be considered as the definitive solution for the identified research problem.

To this regard, Carpenter highlighted the need for a focussed characterization of resilience, able to answer the questions of “resilience of what?” and “resilience to what?” [42]. This posits another dilemma, which is the scale of applicability of the chosen resilience approach. Indeed, district-level schematizations of resilience cannot address the building-specific problem of assessing seismic performance from a structural perspective. On the other side, there appears to be a scattered literature dealing with single-hazard approaches resulting to a consistent disagreement on which is object expected to exhibit resilience and to which stressor resilience has to be developed for [43].

It is therefore pertinent to outline that the main difference featuring the two categories pertaining to the quantitative approaches consists in their target for resilience assessment. Namely, as it can be seen in Figure 2.1, multi-hazard strategies are generally associated to high-level applications whereas resilience assessment entailing a single building are usually carried out in face of a specific hazard.

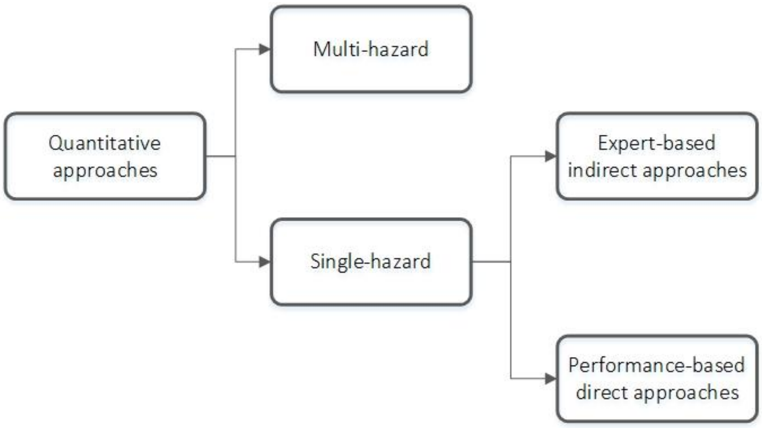


**Figure 2.1:** Categorization of quantitative resilience assessment strategies

This is reasonable given that generally wide-scale approaches factor in a wide range of socio-political and organizational criteria which encompass the characterization of disaster mitigation and management rather than the specific performance of a single structure or infrastructure. For the scope of the presented research, the sole single-hazard category is taken into consideration.

Within this classification, a further distinction is possible as in accordance to Figure 2.1 the identified approaches are the following:

- Expert-based indirect approaches;
- Performance-based direct approaches;

The most evident difference amongst the above approaches consists in the technique employed to quantify performance in face of the targeted hazard. While expert-based approaches draw on a series of representative indicators to then infer a resilience assessment, the others rely on fragility curves and therefore expressing in probabilistic terms the likelihood of exceedance of a specific damage state. These approaches are further explored in the ensuing subsections.

Table 2.2 presents a breakdown of the analysed numerical approaches considered in the current section with regard to resilience assessment in face of geo-environmental hazards and pertaining buildings. The research works are grouped according to the above categorization therefore featuring performance and expert-based approaches. It is noteworthy to mention that the featured approaches address the impact of hazards on buildings and not the built environment in its whole.

**Table 2.2:** Classification of quantitative approaches according to hazard typology and pertaining buildings.

| Category | Reference | Landslides | | | Earthquakes | Floods |
|---|---|---|---|---|---|---|
| | | *Slow-moving slides* | *Rock falls* | *Rapid flow-type slides* | | |
| Expert-based approaches | Uzielli et al. [78] | x | | | | |
| | Kaynia et al. [63] | x | | | | |
| | Karamouz and Zahmatkesh [83] | | | | | x |
| | Field et al. [5] | x | x | x | x | x |
| Performance-based approaches | Barberis et al. [76] | | | | x | |
| | Mavrouli et al. [74] | x | x | x | | |
| | Biondini et al. [101] | | | | x | |
| | Haugen and Kaynia [102] | | | x | | |
| | Kircher et al. [59] | | | | x | x |
| | Cimellaro et al. [66] | | | | x | |

Additionally, the different approaches are further grouped in relation to the hazard they address, namely landslides, earthquakes or floods. Landslides appear to be further divided into three categories due to the different nature of the specific events and speed of the flow (i.e, rapid or slow- flow slides), but also according to the solid fraction of the slide (e.g., rockfalls).

### 2.3.1. Expert-based indirect approaches

As previously illustrated, this category groups those methodologies deriving resilience based on a series of criteria scored subjectively and then combined. An illustrative example can be found in the work by Uzielli et al. [78] where resilience of buildings in face of slow-moving earth slides in Ancona is investigated. Drawing on the collaboration with the Ancona municipality, the authors were able to develop a model to assess the degree of loss undergone by the buildings in the aftermath of the landslide. The Ancona landslide consists in a slow-moving phenomenon which affects the buildings lying on that terrain rigidly rather than dynamically. The authors based therefore the work on the assumption that the displacements undergone by the structures over time did not surpass the ones of the soil underneath.

Uzielli et al. identified structural typology, type of foundation and year of construction as pivotal criteria for the calculation of resilience and by the assignment of weights (i.e., numerical relevance), a final score is then calculated. The relevance of each indicator was established thanks to the contribution of domain experts and members of the Ancona municipality. However, the introduction of a subjective scoring may lead to a higher margin of error. Furthermore, although the criteria identified by Uzielli et al. provide a good picture of the overall buildings' conditions, some equally influential features relatively to resilience are neglected. It is the case for instance of the maintenance condition and the frequency of the interventions, but also whether a building underwent any interventions to comply with current regulations. Despite the flaws identified above, the backbone of the methodology proposed by Uzielli et al. represents a valuable tool for quick resilience estimations prior to more in-depth analyses.

Equation 2.1 displays the formulation of resilience R advanced by Uzielli et al. where $\delta_j$ represents a binary variable whereas $I_j$ stands for a generic resilience indicator conditional on the evaluated building feature (i.e., construction date, foundation type or structural typology). The fraction represents instead the weight assigned to a specific j-th resilience indicator $I_j$ and calculated based on the relevance coefficient $\varphi_j$ which has an allowed variability between 0 and 1. In the context of this approach, the greatest contribution to resilience is attributed to the structural typology, being assigned the highest relevance coefficient. Foundation typology and construction date respectively follow in terms of impact.

$$R = \sum_{j=1}^{n} \left( \delta_j \cdot \frac{\varphi_j}{\sum_{j=1}^{n} \varphi_j} \cdot I_j \right)$$

**Equation 2.1:** Formulation of resilience proposed by Uzielli et al. [78]

Kaynia et al. [63] tackled the assessment of vulnerability in landslide-prone areas although not pursuing the resilience path. Conversely to Uzielli et al., in this approach the dynamic component is chosen and therefore the landslide velocity becomes relevant undermining the equality between the shifts undergone by the superstructure and the underlying soil. Another distinguishing feature consists in the consideration of the maintenance condition of the building which was not overlooked in the methodology devised by Uzielli et al. [78]. The distinctive classification of structural typologies devised by Kaynia allows to factor the site specificity of local construction raw materials. This becomes of crucial relevance when dealing with sustainability, not just resilience, as it is advised to make the most of local resources so that to reduce additional environmental impact due to the transportation of material.

Karamouz and Zahmatkesh [83] adopt a parametric expert-based strategy to evaluate resilience and improve resource allocation following to a flooding event in coastal areas. Factoring both vulnerability and resilience, this approach stands out given its holistic stance. The governing indicators to assess both vulnerability and resilience in the occurrence of a flood event are attributed a relevance conditional on a normalized weighting factor. The approach devised by Karamouz and Zahmatkesh draws on the "four Rs" (i.e., robustness, redundancy, rapidity and resourcefulness) formulation of resilience devised by Bruneau et al. [7] and it extends their applicability to a series of domains of society. Equation 2.2 represents the numerical formulation for resilience achieved by Karamouz and Zahmatkesh, evidently featuring the above mentioned four Rs in the first summation which consequently leads to the development of 4 different equations each producing one of the resilience distinctive components. The expression $\sum_{n=1}^{N_I} \overline{d_n} \cdot (v_{obs}) \times w_{I,c}$ is functional to obtain the system resilience in function of the indicators $N_I$ and of the criterion c. The product $\overline{d_n} \cdot (v_{obs})$ generates non-dimensional values in relation to every observed value $v_{obs}$ and for each resilience indicator $I$. The incidence of each resiliency component on the whole assessment is derived from the ratio between the total amount of indicators $N_I$ and the resilience features $N_R$. Similarly to Uzielli et al., the contribution of each indicator is scored and weighted in this case with the coefficient $w_{I,c}$.

$$R = \sum_{i=1}^{4} \frac{1}{2} \times \left[ \sum_{n=1}^{N_I} \overline{d_n} \cdot \left( v_{obs} \times w_{I,c} + \frac{N_I}{N_R} \right) \right] \quad , i \in [1,2,3,4]$$

**Equation 2.2:** Resilience formulation proposed by Karamouz and Zahmatkesh [83].

While the approach devised by Uzielli et al. led to a more straightforward linkage between resilience and its determining factors, (i.e., building features), Karamouz and Zahmatkesh relate the two indirectly through the calculation of the "four Rs". In accordance to the initial statement regarding the need for a more focussed resilience formulation, perhaps Uzielli's approach succeeds at this pursuing this objective.

The framework developed by Field [5] is worth to be mentioned given its holistic consideration of resilience and applicability in multi-hazard conditions. The resilience measured in this framework is not building-specific but it brings the discourse on a disaster-management level, involving not just technical aspects but also social, environmental and governmental. Here, buildings are not considered the main target for resilience as it was for the previous approaches, but they are involved as part of the urban system and therefore the level of specificity decreases with the extent of the considered scale. Field's strategy entails a six-step methodology initiating with an assessment of the potential hazard which then informs the appraisal of the resilience demand. Once proper measures have been taken to foster hazard mitigation and to enhance the overall resilience, it is possible to compare the effective resilience capacity with the initially evaluated demand by simply calculating their ratio. The resulting value represents the resilience rating and it provides a measure of the improvements attained after the introduction of the hazard mitigation strategies. Subtracting the resilience demand the capacity highlights instead the margin of improvement. Field's framework, similarly to Karamouz and Zahmatkesh, attains a measure for resilience through the combination of different criteria although Field's approach is more versatile. On a different note, approaches such as Field's one lack of scalability as they are not provided with the necessary algorithms and criteria to deal with small-scale (i.e., building-level) resilience assessments.

Following to the above considerations, it can be observed that expert-based approaches factor in the judgement subjectivity while scoring the governing resilience criteria therefore reducing the level of accuracy. The existing body of research with respect to these approaches appears quite scattered spacing to very detailed methodologies to quite broad ones, missing the intermediate link. However, it must be observed that semi-statistical approaches such as Uzielli's one exhibit a significant applicability when targeting a considerable amount of buildings, hence widening the scale of the assessment from the individual town to the regional scale for example.

### 2.3.2. Performance-based direct approaches

The approaches analysed in this section draw mainly on the employment of fragility curves in order to numerically assess resilience. This leads to a continuous representation of the overall building performance, conversely to the discrete one attained by expert-based approaches. The strategy proposed by Mavrouli et al. [74] exemplifies this proposing a methodology for the vulnerability assessment of RC structures when potentially subjected to three landslide typologies (i.e., rapid flow-type, rockfalls and slow-moving landslides). The more focussed scale of analysis compared to expert-based approaches results in the consideration of a more significant level of detail. Consequently, the set of variables adopted to assess the vulnerability are merely represented by frame or material-related features. Steel strain is employed as a performance indicator for the identification of the achievement of a specific damage level.

The work by Cimellaro mainly encompassed seismic resilience for healthcare facilities, such as hospital systems. A distinguishing feature of the proposed works consists in the ability of coupling a performance-based structural assessment to an organizational evaluation in the occurrence of a disruption [39, 66, 103]. Furthermore, the focus on healthcare facilities is particularly of interest given their key role when a hazard occurs, which is also mirrored by the label of "critical infrastructures". As formerly alluded to in the section, the structural performance is assessed by the adoption of fragility curves which measure the probability of exceedance of a specific damage state in relation to a response variable [104]. To this regard, fragility curves were also employed targeting recovery processes and resilience analysis [76] relating the damage state to the intensity, conversely to traditional approaches dealing just with the latter. Through the consideration of three damage states (i.e., fully operational, moderate damage and severe damage conditions) the restoration functions are calculated highlighting that an increase in the seismic intensity would affect functionality and hinder reconstruction, expanding the time schedule for recovery. An additional conclusion is drawn with respect to the failure mechanism, where a brittle failure corresponds to a lower resilience (i.e., ductility) level.

Biondini et al. [101] derive a time-dependant equation of a building's performance in seismic conditions by calculating the ratio of the acceleration bearing abilities at a given time ($a_g(t)$)and the event's measured acceleration ($a_{g,0}$), as shown in Equation 2.3. The authors take into account functionality losses, providing also a numerical assessment of the effective resilience capacity of the structure from a mainly dynamic perspective.

$$Q(t) = \frac{a_g(t)}{a_{g,0}}$$

**Equation 2.3:** Calculation of time-dependant seismic performance [101]

Bruneau and Reinhorn [61] propose a methodology to calculate resilience adopting floor accelerations and inter-storey drifts as indicators of the building seismic performance. Once probability performance contours have been defined and intersected with limit states, a measure of resilience can be attained as well as the calculation of fragility curves. However, this methodology becomes relatively cumbersome given the necessary integration with a purely mathematical skeleton that might be of challenging application in the industry domain.

HAZUS [59] consists in a methodology to assess the damage to buildings in face of single or multi-hazards conditions. Mainly it addresses the consideration of earthquake-triggered geo-environmental secondary effects, such as landslides or inundations, however no targeted models were developed specifically regarding floods, landslides or extreme wind conditions. Resilience is here factored indirectly and non-explicitly through the combination of the building capacity curves and demand spectrum. This results in the derivation of the fragility curves pertinent to each damage state and therefore the discrete probability of occurrence.

It is evident in these contexts the analogy between "resilience" as property of a building when affected by a hazard and "ductility" as it was described in the context of the tensile steel diagram. As alluded to formerly, ductility can be easily assimilated to resilience from a building performance perspective. Ductility in fact reflects the concept of evolutionary resilience meaning the ability of a system to endure the effects of external stressors. While in the context of steel the elastic deformation is not recoverable once yielding is exceeded, a resilient system can proactively attain a new stable performance level not necessarily analogous to the pre-disruption one. As shown by the presented approaches, fragility consists instead in an undesired property given its unpredictable and sudden occurrence which is a flag for the incapability of the structure to adapt [105]. A brittle failure in a structure undergoing dynamic (but also static) stresses, such as an earthquake, results in the impossibility of occupants to be warned about the imminent collapse. In this sense, a fragile structure is the negative correspondent of a ductile one and similarly can be maintained when comparing a brittle system to a resilient one.

When tackling the structural design of buildings and in accordance to the above, ductility and resilience can be considered related but not equivalent. It is acknowledged that both performance-based and semi-probabilistic approaches factor in a certain level of uncertainty in relation for instance to seismic events, when the occurrence and intensity it is established on a statistical basis. Furthermore, modern performance-based regulatory frameworks [33, 106–108] prescribe a design grounding on an expected ductile behaviour of buildings capable of exploiting the plastic capacity and not just relying on the elastic one. There is a demand for buildings to therefore perform adaptively and being capable of enduring different disruptive events with preferably minimum recovery interventions. Having said that, an effective resilience planning has to be risk-aware and able to factor in site-specificities as well as foreseeing potential damages and recovery strategies with consequential costs. This results in picturing resilience as a more comprehensive feature than just ductility itself, as it is considerate of the whole building lifecycle and not just of its performance demand. This posits the following question: how resilience can be effectively included into long-term strategies for building design, maintenance and recovery in face of seismic hazards and in a concretely applicable way?

### 2.3.3. Summary

The scope of Section 2.3 has been to investigate whether the two analysed approaches (i.e., expert and performance-based) could fit the research purpose and specifically aid the development for a methodology leading to answer Research Question 2-4.

Expert-based approaches overall are not successfully able to characterize resilience in a univocal manner, given the sometimes high degree of uncertainty involved in the scoring process. This is also similar to the approach adopted by qualitative frameworks, although expert-based methodologies target buildings' performance specifically and capture the level of detail that would feature resilience micro-scale approaches. Conversely, performance-based approaches can successfully represent the expected buildings' performance once established the external stressor's magnitude, given their stochastic nature. Besides, performance-based approaches can also factor building resilience compliance as opposed to subjective expert-based strategies.

Additionally, expert-based approaches tend to decompose the building system in different features (e.g., foundation system, structural technology and geometric irregularity) whereas performance-based techniques can effectively qualify the type of behaviour and failure. This allows to comprehensively evaluate the expected or effective performance of a building factoring in inter-correlations between variables and without disregarding specific features, conversely to what instead could happen when adopting a fragmented subjective approach.

Overall, when adopting expert-based methodologies, resilience is identified discontinuously given the fragmented nature of these approaches. Conversely, performance-based methodologies manage to pursue a representation of the buildings' performance which can fit the scope of a micro-scale approach demanding for higher level of detail. Grounding on the above considerations, performance-based approaches appear to be more suitable for the scope of this research, being able to factor the high interconnectivity across the variables determining the overall structural behaviour.

## 2.4. Assessing the damage to buildings

Section 2.3 highlighted a stronger potential for applicability in the context of this research for performance-based approaches. However, the adoption of a performance-based approach needs to consider the concept of damage assessment and how it is conducted in this context. Nonetheless, it is relevant to explore how damage to buildings is usually assessed from a wider perspective as one of the drivers for this research is represented by the capacity of integrating micro and macro scales of analysis. This entails the consideration of different set of variables and consequently, different levels of details according to the scale of analysis.

The damage to buildings is usually assessed either qualitatively or analytically. The first strategy entails the identification of specific damage typology and level based on experience and visual appraisals, while the analytical approach entail more rigorous calculations and simulations. This section will therefore address in detail these two approaches, contextualizing them in relation to the pertaining literature and regulatory frameworks. The characterization of these approaches is key to integrate the two aspects of the proposed framework, namely entailing a qualitative and quantitative assessment of resilience. The first sub-section addresses the identification of explicit targets for performance indicators, while the second one will entail the consideration of qualitative damage assessment scales.

### 2.4.1. Engineering Demand Parameters

Measuring the level of performance of a structure is a not a straightforward process as it entails the consideration of significant amount of variables with mutual impact and interdependencies. Standard practice usually requires to identify indicators to univocally represent the level of performance of a building in face of a specific hazard, namely Engineering Demand Parameters (EDPs) [109]. The identification and characterization of these variables is also functional to benchmark the results attained while performing optimization strategies, as it will further explored in the following section.

An EDP is a parameter whose value results from the structural behaviour simulation and it used either for regulatory compliance [110] or in combination with computational techniques. Overall, the literature evidences that EDP can be labelled either as “global” or “local” according to the structural element they refer to. Examples of local EDPs can be chord rotations or node displacements, while within global EDPs it can listed the inter-storey drift ratio (IDR). While the concept of node displacement is rather straightforward as it entails the absolute displacement of a structural node (i.e., the intersection of two or more structural members), the IDR is not directly measurable. The inter-storey drift ratio is in fact calculated as the relative drift between two subsequent storeys, divided by the storey height [111–113] and it is usually represented as a percentage value.

Performance-based design extends the expected structural performance over the elastic capacities, considering also plastic resources and hence its deformability under prolonged stress. Calvi proposes an extensive overview of displacement-based design [114] underlining how often poor seismic performance stems from an underpinning lack of ductility rather than an excess of horizontal force. A preliminary establishment of the expected ductility, hence displacement, leads to a more effective control of the building performance over time. Calvi therefore defines displacement-based limit states featured by corresponding damage levels and non-structural failures as a consequence of both drift and acceleration. Both masonry and RC frames are considered in Calvi’s approach, however just the latter are considered herein given the focus of this research as summarised in Table 2.3.

Table 2.3 differentiates in fact between regulatory frameworks and relevant academic-based approaches, consisting in the ones proposed by Calvi [114] and Ghobarah [115]. In terms of building regulations, FEMA 356 [107] and SEAOC Vision 2000 [108] represent the featured American regulatory frameworks, whereas Eurocodes [106] and Italian standards [33] are considered in relation to Europe. A first consideration in terms of distinguishing features between European (i.e., Eurocodes and Italian standards) and American standards is evident relatively to the replacement of the IDR for Life Safety and Collapse verifications. Eurocode 8 namely involves chord rotations while Italian standards require ductility, stability and resistance verifications.

**Table 2.3:** Inter-storey drifts limits according to different building regulations and literature.

| | | | | | | |
|---|---|---|---|---|---|---|
| **FEMA 356** [107] | **DS** | Immediate occupancy | | Life Safety | Near collapse | |
| | **EDP** | IDR | | IDR | IDR | |
| | **δ** | 1% transient or negligible | | 2% transient 1% permanent | 4% transient or permanent | |
| **Eurocode 8 §4.4.3.2** [106] | **DS** | SLS (serviceability) | | ULS (ultimate) | | |
| | **EDP** | IDR | IDR | Chord rotations | | |
| | **δ** | 0.5%, 0.75%, 1% | 0.5%, 0.75%, 1% | | | |
| **SEAOC Vision 2000** [108] | **DS** | Fully operational | Operational | Life Safe | Near Collapse | Collapse |
| | **EDP** | IDR | IDR | IDR | IDR | IDR |
| | **δ** | <0.2% transient Permanent negligible | <0.5% transient Permanent negligible | <1.5% transient <0.5% permanent | <2.5% transient or permanent | >2.5% transient or permanent |
| **NTC 2018** [33] | **DS** | SLE (serviceability) | | SLU (ultimate) | | |
| | | SLO (operational) | SLD (damage) | SLV (life safeguard) | SLC (collapse) | |
| | **EDP** | IDR | IDR | Ductility, resistance and stability verifications | | |
| | **δ** | 2/3 $IDR_{SLD}$ | 0.5%, 0.75%, 1% | | | |
| **Calvi** [114] | **DS** | LS1 | LS2 | LS3 | LS4 (collapse) | |
| | **EDP** | IDR | IDR | IDR | IDR | |
| | **δ** | 0.1%÷0.3% | 0.3%÷0.5% | 0.5%÷1.5% | >1.5% | |
| **Ghobarah** [115] **IMRF** | **DS** | Repairable damage | Irreparable damage | Severe damage/Life safe | Collapse | |
| | **EDP** | IDR | IDR | IDR | IDR | |
| | **δ** | 0.2÷0.4% | >0.4% | 0.7% | >0.8% | |

With respect to Eurocodes, different benchmark values for the IDR are provided for serviceability verifications, depending on the level of ductility and correspondingly increasing from 0.5% to 1.5%. Similarly, the Italian Ministerial Decree of 2018 establishes a similar procedure for Damage State (DS) (i.e., SLD) verifications, although being stricter than Eurocode 8. In terms of Operational Limit State (SLO), the Italian standard limit the IDR to a value corresponding to 2/3 of the IDR calculated for the subsequent limit state. This procedure, differently from other regulations, creates a dynamic interdependency across the limit states pushing for a better performance at more demanding limit states. This is also motivated by the need of realising structures able to withstands medium-low seismic actions being them characterized by a lower intensity, hence a higher probability of occurrence in terms of return period [116].

It is pertinent to mention that other research works have also adopted the inter-storey drift ratio as a benchmark parameter to identify the structure’s performance. This is the example of Bruneau and Reinhorn [61] who adopted a probabilistic distribution surface where the achievement of specific limit state (i.e., cracking or collapse) is defined by floor pseudo-acceleration and inter-storey drift. IDR ratio is also adopted as a performance index for the definition of each limit state in the research devised by Möller et al. [117]. Namely, the performance level defined as “operational” differs from the others entailing an elastic behaviour because the structure is not supposed to have achieved its plastic capacity. Conversely, the maximum inter-storey drift is factored in all three limit states as a meaningful EDP. Aslani and Miranda [118] propose instead a PEER-based methodology to assess the minimum number of response history analyses to reliably evaluate probability parameters able to represent a building’s structural response. This is pursued adopting two response variables, consisting in the IDR and the Peak Storey Acceleration (PSA).

### 2.4.2. Damage scales

Qualitative approaches to characterise the damage to building subjected to geo-environmental hazards are not analytical methods and their output reflects a certain degree of subjectivity, hence error. The latter consists therefore in a subjectivity error, which derives from the consistent human-related uncertainty resulting from the expert-based assessment addressing the relevance of specific indicators.

However, the applicability of such techniques is wide when a prompt assessment of the overall disrupted configuration has to be made. These approaches rely in fact on mainly visual appraisal of building features and recurrent structural behaviours based on existing patterns pertaining the specific structural typology and the hazard. Besides, the adoption of qualitative damage scales provides the key bridging feature between the building and district-scale resilience assessment, as the two can be combined to attain a comprehensive damage scale inclusive of both the qualitative and analytical aspects.

For the purpose of this research and considering the main focus of this research for geo-environmental hazards, pertinent damage scales are considered. Table 2.4 presents to this respect an overview of the analysed damage scales and their target hazard and the pertaining DSs. Given the need to apply the damage scale in a context where both earthquake and seismically-triggered side effects occurred, the review involved both damage scale typologies.

The presented damage scales also provide a description for each Damage State (DS), which mainly coincide across the damage scale for the same DS. The majority of them entails the consideration of 5 DSs while just 2 of them devise 6 levels mainly due to the consideration of the undamaged condition as a starting DS. The European Macroseismic Scale EMS 98, coherently with similar approaches target seismic hazards, adopts a 5-level damage scale. The 4-DS scale proposed by Kang et al. [122] represents an anomaly in terms of both DSs, including just the following fuzzy labels: slight, moderate, extensive and complete damage. Namely, in the other damage scales the equivalent “moderate” damage level appears as split into two separated levels. However it is acknowledged that this approach entails the consideration of fuzzy concepts as opposed to analytical evaluations, therefore a certain level of disagreement across the adopted approach is expected.

**Table 2.4:** Overview of reviewed damage scales for qualitative damage building appraisal.

| Author(s) | Construction typologies | Hazard | Damage States (DSs) |
|---|---|---|---|
| Hu et al. [119] | RC frames, composite masonry/RC | Debris flows | 5 |
| Mavrouli et al. [74] | RC buildings | Landslides | 6 |
| Okada and Takai [120] | Masonry load bearing structures, RC frames | Earthquake | 6 |
| EMS-98 [121] | Masonry load bearing structures, RC frames, wood frames, steel | Earthquake | 5 |
| Kang et al. [122] | Masonry load bearing structures, RC frames, wood frames | Debris flows | 4 |
| Leone et al. [123] | Not specified | Landslides | 5 |
| Calvi [114] | Masonry load bearing structures, RC frames | Earthquakes | 5 |
| Medvedev and Sponheuer [124] | Masonry load bearing structures, RC frames, wood frames, prefabricated | Earthquakes | 5 |

With respect to seismic-related damage scale, the approach proposed by Okada and Takai [120] was included given its applicability to different structural typologies, entailing a certain level of versatility. The scale proposed by Medveded and Sponheuer [124] consists in perhaps one of the most comprehensive as, similarly to Calvi [114]and the EMS 98, it devises an extensive description of the damage for each structural typology in relation to the specific DSs. Calvi operates in a similar manner, however its consideration is limited to masonry load bearing building and RC frames, representing however a great proportion of the existing building stock and being particularly prominent in the context of performance enhancement and restoration.

As far as landslides and debris flows are concerned, the approach proposed by Mavrouli et al. [74] consists in the most comprehensive amongst the ones analysed in this category. Its combination of analytical simulations inclusive of both structure and terrain as well as the consideration of structural and non-structural element are distinguishing features. The consideration of the scale proposed by Hu et al. [119] is motivated by its development based on a debris flow event in Zhouqu (China). This scale also grounds on the China's Classification System of Earthquake Damage to Buildings [125].

### 2.4.3. Summary

This section aimed at providing an overview of strategies for damage assessment to buildings including both performance-based approach targets (i.e., EDPs) but also involving qualitative damage scales. The consideration of both of them, and not just EDPs, stems from the need of integrating in this research building and district-level approaches and evaluate the potential for their combination in the context of damage assessment. To this respect, the literature analysed in relation to engineering demand parameters allowed to identify two main indicators, namely node displacement and IDR.

In order to systematically evaluate which of the analysed EDPs better fits the purpose of this research by aiding a more accurate structural behaviour analysis, both of them are considered and eventually the choice will be operated based on the results. This decision stems from the need of adopting a rigorous approach and not grounding the choice of the EDPs just on qualitative considerations.

On a different note, the analysis of semi-qualitative damage scales revealed an effective way of correlating qualitative and analytical damage assessment to buildings. This is pursued by associating fuzzy damage levels characterization (e.g., low, medium, high, and collapse) to the numerical value of the EDP selected for the analysis. Usually, the damage attained for a corresponding EDP value can be identified as limit state (LS). Limit states are usually adopted by regulatory frameworks to identify the benchmark condition and provide the corresponding EDP limit value. However, amongst the analysed building regulations, different values are sometimes adopted for the same LS and some of them, such as Eurocodes, prescribe different benchmarks variables for different LSs.

However, it is maintained that providing a correspondence amongst the effective damage and a fuzzy characterization of the disruption represents an efficacious strategy which could aid damage identification and forecasting. Consequently, this research would benefit from the definition of a series of LSs (or damage levels) to which specific EDPs would correspond and therefore enable a more straightforward scalability of the methodology and its applicability also for visual damage appraisals.

## 2.5. Artificial intelligence applications in structural engineering

Capturing the expected buildings' performance is key when tackling with seismic hazards determining the design of the structure and it represents the essence of performance-based engineering. Performance-based approaches factor a certain degree of uncertainty with respect both to the hazard and the building's performance [126] and this strategy paved the way for a new research thread that aims automating certain tasks of the buildings' analysis. Structural engineers and practitioners are however more reluctant to integrate these approaches in common practice, compared to the fat-growing trend in research for this domain. Grounding on the above, this section aims at exploring the commercial software available for structural analysis in buildings and at the same time it reviews some popular optimization tools which are adopted in common practice and research. Following to this, meaningful applications of machine learning and dimensionality reduction techniques are analysed.

### 2.5.1. Commercial software for optimization and structural behaviour simulation

Several commercial tools for structural behaviour simulation are available in the market and can be broadly categorized according to the construction technology they address, as shown in Table 2.5. As shown in the table, the majority allow a versatile modelling of the structural technology, exception made from ADAPT which is specifically devised for RC constructions. However, few of them are provided with optimization plug in or tools to enable this process.

Perhaps, a good example is GenerativeComponents [127, 128] commercialized by Bentley, which aids a topology optimization process allowing the exploration of a vast range of design choices. Another example of topologic optimization is provided by SMARTSizer which exploits the API of Autodesk Robot Structural Analysis in order to perform optimization tasks but forcing the user to export the results in an Excel spreadsheet [129].

**Table 2.5:** Categorization of relevant structural behaviour simulation software.

| Software | Software house | Construction material | Seismic simulation | Optimization tool | Optimization strategy |
|---|---|---|---|---|---|
| SCIA | SCIA - Nemetschek Company | Multi-material | X | / | / |
| SAP2000 | CSI – Computers and Structures | Multi-material | X | / | / |
| Autodesk Robot Structural Analysis | Autodesk | Multi-material | X | SMART Sizer [129] | Topology/size |
| ADAPT | ADAPTsoft | Reinforced Concrete | X | / | / |
| MasterSAP | AMV | Multi-material | X | / | / |
| Midas | MIDAS Engineering Software | Multi-material | X | / | / |
| Tekla | Trimble | Multi-material | X | | |
| Structural Enterprise | Bentley | Multi-material | X | GenerativeComponents | Topology/size |
| SODA | Waterloo Eccentric Software | Steel | X | X | / |
| OpenSees | Berkley University | Multi-material | X | / | / |

Furthermore and similarly to the optimization tools categorized in Table 2.6, the main purpose of the existing tools entails the design of new constructions. It is pertinent to mention that OpenSees [130] is listed amongst the commercial tools although being open source. To this regard it is considered appropriate to include it given its established position in the industrial but mainly academic domains specifically for seismic-related analyses.

An accomplished example of structural software able to couple optimization and code checking can be identified in SODA [131] which also has an already established market of users in both the US and Canada. Nonetheless, the limitation to a single structural technology can represent a constraint when the intention is to adopt different materials. Some of the software presented in Table 2.5 are also listed in Table 2.6 given their relevance in terms of optimization purposes, and SODA is amongst them as well as Autodesk Robot Structural Analysis and Bentley GenerativeComponents.

Grasshopper, on the contrary, while listed amongst the structural simulation tools consisting in a parametric design tool, was not initially conceived for structural analyses purposes. It was initially developed as a plug in for Rhinoceros and it represents a tool for parametric design. One of the available plug ins for Rhino, Galapagos [132], allows optimization to be performed on the structure [133] mainly from a topologic perspective and similarly to what proposed by SMARTSizer.

**Table 2.6:** Classification of optimization tools.

| Software | Objective | Performs structural analysis | Optimization tool | Algorithm | Optimization strategy |
|---|---|---|---|---|---|
| SODA | Design | X | - | - | - |
| Rhino [136] | Design | X (Karamba) | Galapagos | Evolutionary algorithm | Topology/size |
| Bentley | Design | X | GenerativeComponents | - | Topology/size |
| Robot | Design | X | SMART Sizer | - | Topology/size |

Table 2.6 also evidences another tool available in the Rhino suite, namely represented by Karamba [133, 134] and consisting in a finite elements analysis engine. A drawback highlighted both relatively to Galapagos [132] and Karamba [133] is represented by the running time of each optimization [135], which becomes a consistent issue when adopting evolutionary algorithms. This happens mainly due to the adoption of the software as it is the continuous iteration of a considerable amount of simulations that occupies a long time frame. A criticality of optimization problems in general is represented by the likelihood of often identifying the local optimum instead of the global one, without hence being able to identify the effective best solution to fit the optimization problem. Oftentimes this results in longer computing times and this is highlighted in relation to Galapagos, where the time required to evaluate the global optimum even though the convergence area has been identified [135].

In light of the above, it is evident how the majority of structural software have not yet been provided with the potential for optimization and when there is, evident limitations regarding potential applications are highlighted. In fact, there is a common trend in implementing topology and size optimization, however this evidently constrains the applications to design solutions and hence new constructions. Grasshopper in particular represents one of leading tools for parametric and size optimizations. Its bespoke optimization tool, Galapagos, is widely used to perform sizing optimization in complex structures, such as diagrids [135].

Furthermore, the majority of exiting tools mainly deals with design-related optimization, while the versatility featuring the proposed methodology is represented by the capability of addressing both new and existing buildings. The application of the proposed research strategy would fulfil the exploitation of the computational potential for optimization and hence the exploration of a consistent number of design options.

### 2.5.2. Machine learning for structural optimization

While in the past structural engineers could not exploit the potential of software in order to boost their design capacities, nowadays it is a standard requirement given the increasing complexity in buildings' geometry and consequently in calculation nonlinearity. Therefore, being able to rely on a computational tool relieves professionals from performing cumbersome and sometimes repetitive calculations. However, before the spread of structural behaviour simulation tools, machine learning and optimization processes were considered as a disjointed task respect to the main structural calculation.

Specifically regarding the employment of ANNs, the extensive review provided by Abiodun et al. [137] evidences how the application of neural networks is nowadays well-established in a number of domains. Engineering appears to exhibit amongst the highest amount of applications with respect to prediction, appearing to be one of the domains where the potential of ANN is exploited the most [137]. To this respect, applications in engineering stretch out to different fields, from the design and optimization of a single element to a whole structure. Perhaps, the first implementation of neural computing into structural design was devised by Adeli and Yeh [138] with the design of a simply supported beam subject by uniformly distributed load in combination with PROLOG and PASCAL languages. The benefits of adopting artificial intelligent techniques was evidenced by the reduced calculation times and the ability of factoring the experience of a professional. The integration of ANNs with evolutionary computing techniques is also pinpointed in the review and acknowledged as an advantageous approach. The combination of an ANN-GA ensemble have been exploited before, although with significant computational demand [139]. Topping et al. [139] propose an utilization for this strategy in the domain of meshing partitioning and finite elements analysis (FEM). Moselhi et al. [140] address instead decision-making processes devising a tool aimed at aiding the creation of bids.

Genetic algorithms are also employed to optimize the shear capacity and location of dampers under seismic actions targeting the building' IDR an objective for the iteration [141]. Research evidence the adoption of GAs in the optimization of trusses [142] but also tall steel structures, although it is acknowledged the high number of simulations required to attain the optimum solution [143]. An interesting application of GAs is also demonstrated by their employment for design optimization of shading, in combination with Rhinoceros and Grasshopper [144]. Architectural design represents a fertile domain for the deployment of GAs, given the opportunity of investigating a wide variety of shapes adopting topology and size optimization strategies and often in combination with parametric software [145, 146].

More recently, neural networks have been adopted for damage assessment [147] and prediction, but also as tools for bespoke design. Tahir and Mandal propose to this regard a methodology to assess and predict cylindrical structures under axial load involving a backpropagation artificial neural network trained through Bayesian regression [148]. They adopt the MATLAB artificial neural network toolbox and train a neural network that can adjust the thickness of the cylinder based on the axial load and the expected buckling. Within the field of tubular columns, Ahmadi et al. devise an ANN-informed methodology to assess the capacity of cylindrical steel elements filled with concrete [149]. The authors, similarly to Tahir and Mandal, tackle the buckling phenomenon derived by the application of axial load relying on a neural network to predict the strength of the structural member based on material and geometrical properties.

Within the seismic domain, damage prediction in reinforced concrete frame is tackled by Morfidis and Kostinakis [150]. The authors adopt a multilayer feedforward ANN to predict and assess damage in frames through a twofold strategy including (i) estimation of damage to buildings and (ii) pattern recognition. Möller et al. propose an optimization strategy for performance-based design of buildings adopting three limit states (i.e., operational, life safety and collapse) each identified by a set of EDPs. The authors also provide different cost-informed scenarios for optimization.

Arslan devise instead a methodology which combines an initial performance assessment with an ensuing ANN-based identification of the most influencing parameters for seismic design of RC buildings [151]. A set of RC structures are modelled and analysed producing capacity curves and the ANN was trained based on a set of variables representing RC building features, namely including: (i) transverse reinforcement ratio, (ii) concrete compressive resistance, (iii) yield stress for steel, (iv) infill wall ratio, (v) short column, (vi) strong-column weak-beam, (vii) number of stories and (viii) shear wall ratio. Despite the novelty of the approach, the transition between the generation of the capacity curves in SAP2000 to the identification of the governing factors for seismic design it is not straightforward and requires manual computation in order to be performed. Furthermore, the author describes how a benchmark across different neural network Training Algorithms has been performed in order to select the one with the best accuracy, however the identification of the best algorithm is case-sensitive as highlighted in the paper. Nonetheless, the lack of automation is this approach might result in significant manual calculations and the need for the user to perform the tasks in the transition phases. Furthermore, the proposed approach may not be suitable for an application in terms of design and might be limited to a post-disaster condition. To this regard and given its evidence-based nature, several buildings are needed in order to provide the neural network with a sufficient amount of data for its training. Consequently, in a real scenario where damage forecasting would need to be carried out it would be difficult to determine a priori the extent and level of damage without relying on past event data.

An interesting approach to drift-based seismic design is proposed by Park and Kwon [152] who formulate an optimization problem for tall steel buildings aimed at minimizing the weight of the structure and constraining IDRs, roof displacements and stresses for frame members. The authors also adopt sensitivity coefficients for eigenvalues and eigenvectors in order to tweak the spectral analysis parameters.

Šipoš et al. [153] encompass seismic damage prediction of a masonry infilled RC frame following the identification of the most common failures. The neural network adopted for damage detection is trained with a series of input describing the geometric relationship between the masonry infill and the surrounding RC frame. A selection of three data reduction algorithms is assessed in order to prevent overtraining and to increase the time-performance. Nevertheless, neglecting the potential presence of windows results in a consistent limitation for the proposed analysis as it assesses the best case scenario of a totally masonry infilled frame. Lessons learnt from past seismic event  [154–157] evidence in fact a correlation between an inadequate percentage of infill, its distribution and the resulting damage on global building scale. In addition, this research results from the collection of a dataset of one bay, single storey masonry infilled frames which is however suitable just for local applications and mainly focusses on masonry not taking into consideration the interaction concrete-masonry which features local models. Additionally, the adoption of a macro-modelling strategy such as Stafford-Smith formulation for a local approximation of masonry in the context of a single frame does not reflect the standard level of accuracy generally accomplished by local analyses. As it will be further explored in section 2.7, the modelling scale with respect to masonry infills has an impact on the involved variables.

A combined engine constituted by MATLAB and OpenSees is devised by Vazirizade et al. [158] with the aim of performing reliability assessment of steel structures in face of seismic hazards. The ANN is trained based on three inputs, namely the inter-story ratios corresponding to each of the building levels. However, this methodology exhibits some consistent limitations, first of all the rigidity of input size for the ANN. Namely, if a building with a storey number different from three was to be considered, the ANN devised in the context of this research would be unsuitable as the input size should automatically reflect the building features. Furthermore, a comprehensive and risk-aware seismic assessment cannot consider just one limit state and namely, the least demanding one as some limitations might occur when upgrading the complexity of the analysis due to the introduction of stricter drift limitations. In fact, the authors considered only the "immediate occupancy" limit state as defined by FEMA 350 [159].

Noteworthy applications of neural networks can be found in the investigation of Fiber Reinforced Polymers (FRP) contribution to a structural member resistance. FRP consist in a relatively novel strategy to reinforce and confine existing structural members (e.g., columns, beams but also masonry) when the effective tensile or shear capacity does not suffice. FRP consist in a polymeric matrix reinforced with fiber and are featured by a significantly high tensile resistance, which provides a significant contribution where the existing structure exhibits a failure induced by an excess of flexural or shear action. Representative research involves reinforced concrete structural members [160–162] and the exploitation of neural networks to assess and predict shear stress with the application of FRP elements. Naderpour et al. investigated the contribution of FRP to the compressive resistance of confined RC members through the application of neural networks to predict the effective capacity [163]. A hybrid neural-fuzzy network created through the combination of an ANN with fuzzy logic capacities is instead adopted by Naderpour et al. [164] to predict the contribution in terms of shear to RC members strengthened by FRP. A combination of artificial neural networks is instead adopted by Köroğlu et al. [165] specifically for columns strengthened around the whole section.

### 2.5.3. Data-reduction techniques and their applications in engineering analyses

Dimensionality reduction strategies are widely employed when an initial large set of data has to be reduced retaining the highest amount of information as possible [166, 167]. Existing literature evidences that data reduction algorithms prove to be effective in machine learning applications [168] but also for engineering-related methodologies [169–172]. The literature distinguishes mainly existing techniques in two categories, namely linear and nonlinear algorithms and the latter can be further clustered into global and local [173]. Examples of linear reduction strategies are for instance Principal Component Analysis (PCA) and multidimensional scaling (MDS). With respect to nonlinear reduction algorithms and referring to local approaches, it is pertinent to mention Locally Linear Embedding (LLE) and Laplacian Eigenmaps, whereas Isomaps can be considered for global approaches [168, 173].

As evidenced by existing literature, PCA is widely employed in engineering applications, such as modal analysis [174] and reduced-order vibration analysis [175, 176]. Several applications are also found in the context of sensor analysis [177] and damage detection [170–172, 178]. With respect to vibration-based engineering applications, it is common to adopt Frequency Response Functions (FRFs) for damage identification, then reducing its output utilizing PCA and adopting the resulting output for neural network training [169, 178]. An interesting application of PCA is proposed by Šipoš et al. in combination with sensitivity analysis, with the final scope of training an ANN for damage prediction and failure mode for a simple masonry infilled RC portal. Bellino et al. present how PCA can be integrated to reduce laboratory tests data in order to assess the level of damage in beam elements subjected to the effects of temperature [171] but also more generically environmental factors [170]. A relevant application of PCA for data reduction is proposed by de Latour and Omenzetter in relation to damage quantification on structures adopting modal analysis.

Similarly, MDS approaches produce a similar output to PCA namely consisting in a linear transformation of the original data which is then projected into the feature subspace [168]. The main difference amongst the two approaches consists however in the preservation of pairwise distances between the objects, in the case of MDS [168].

However, linear methods sometimes fail to provide a representative and reliable reduction as the complexity of the interrelations between the variables is not captured effectively. To remedy these shortcomings, nonlinear versions of PCA were developed, such as Kernel PCA (KPCA) [168, 179]. This is a strategy which stems on the formulating the problem of the covariance construction matrix based in function of the kernel function. Namely, this function replaces the dot products and aids the formulation of the problem in the feature space which would be otherwise infinite-dimensional [168]. Applications of Kernel PCA can be found in structural health monitoring [180], but also structural damage assessment [181].

In light of the above, it is then selected PCA to perform data reduction. This stems from its established adoption compared to perhaps newer techniques (e.g., nonlinear graph methods) and to its wide applicability to a series of engineering-related problems, as the review highlighted. In addition to that, nonlinear graph-based techniques might result more computationally burdensome and the potential for higher sensitivity in the dataset [182]. Additionally, as opposed to nonlinear and inverse algorithms, the transformation between PC space and the original dataset is straightforward when performing PCA as it entails only the introduction of the transformation matrix. On the contrary, strategies such as KPCA rely on a non-explicit variable, hence the transformation between original space and PCs is not as straightforward as in the case of PCA. This would hence result in a higher computational work, hindering the whole framework performance.

### 2.5.4. Summary

The literature analysed in this section provides a clear picture of the state-of-the-art approaches available in research with respect to machine learning-enhanced structural analyses and damage prediction for buildings. The integration of both neural networks and optimization strategies is widely established and there is an increasing trend in their integration. The domain of artificial intelligence and machine learning has been applied extensively to structural engineering in the last years for both optimization and prediction purposes. The introduction of automated optimization strategies naturally led to exploiting the potential for neural network adoption and the implementation of data reduction algorithms to avoid penalizing simulations time. Nonetheless, few are the approaches considering the adoption of commercial software APIs for a smoother integration between the structural appraisal and the optimization tasks.

Regarding commercial software for structural analysis and optimization, it was demonstrated how the latter is not yet fully implemented into practice even though some tools are available to perform the two tasks in combination. Moreover, the majority of the software enabling optimization however limit it to topology and size disregarding the potential for other buildings' properties. On the other side, research evidence the existence of approaches able to factor in the potential consideration of material and mechanical properties of materials, yet not implementing software's APIs. This results in a major shortcoming given the limitations in analyses typologies and scalability of the approaches.

On the other hand, there is a uniform agreement in the integration of data reduction techniques when combining evolutionary algorithms or FRFs and neural networks, given the large amount of generated data. Structural engineering-related applications have started integrating nonlinear strategies for data reduction, such as KPCA, however the mostly established one still remains PCA given the simplicity of application and ease of moving from features and data spaces.

With respect to neural networks, it was evidenced by the review that the neural network technique can effectively benefit the work proposed in this research, given its ease of integration and deployment. Similar considerations can be formulated in relation to genetic algorithms, which are widely employed for optimization in the structural domain given their transferability and accuracy. However, the architectural domain appears to be more willing to integrate optimization tasks to software employment to enhance parametric design, whereas the structural field remains scattered on this position. In addition to the above and in light of the review, the choice of the software for structural analysis is Autodesk Robot, given its established adoption in the professional environment, but mainly because of the interconnectivity between Revit and therefore enabling a smooth file exchange with potential for automation.

## 2.6. Machine learning techniques and dimensionality reduction

It was demonstrated in section 2.5 how machine learning and, more generally, artificial intelligent techniques are widely implemented into modern structural engineering approaches. Moreover, the identification of the algorithms intended to be adopted for the scope of this research was also pursued. To this regard and in order to best characterize the aforementioned techniques, a concise overview regarding each of them is provided.

### 2.6.1. Artificial Neural Networks

Artificial neural networks can be loosely defined as biology-inspired intelligent techniques able to emulate the nervous system capacity to learn [183, 184]. Neural networks have been devised as a mathematical abstraction of the human cognitive system drawing on the exchange of information between simple elements, the neurons [185].

Perhaps, the root of neural computing can be found in the research carried out by McCulloch and Pitts in 1943 [186] where a single neuron network was modelled to provide an output of either 1 or 0 according to its level of activity given a series of inputs. This germinal work was expanded by David Hebb in 1949 and laid the foundations for neural computing grounding on the relationship between biological associative memory and its connections with nerve cells synapses [187]. Stemming from Hebb's research, later on in 1958 Rosenblatt advanced his model of "Perceptron", the first translation of a biological system into a single-neuron computational ensemble capable of learning [188, 189]. According to recent reviews [190, 191] the field of neural computing underwent a significant arrest due to the critical appraisal released by Minsky and Papert in 1969 drawing the attentions to the limitations of "Perceptron", of them consisting in the exclusive-or problem [138]. Nonetheless, the work devised by Kohonen and Anderson in 1972 [190] endorsed the appeal of neural computing towards the research community. It was after 1982 though that the interest in neural computing and its applications registered its highest peak [191] and namely after the work by Hopfield [192] who highlighted how to address the limitation of the model proposed by Hebb and the ensuing critique by Minsky and Papert [191].

Despite the initial hindering, Artificial Neural Networks (ANN) are nowadays widely applied in research given their ability to fetch patterns and provide accurate predictions. Stemming from their biologically-inspired origin, ANNs can be broadly defined as a complex ensemble of basic computing nodes (i.e., neurons) connected and layered in a way to resemble the synapses of a living being's brain [190, 193]. Similarly to the seminal work by McCulloch and Pitts, the neurons constituting modern ANNs produce a signal (i.e., output) when a pre-defined threshold for neuron is exceeded [190]. Hajela and Berke further explain that the biological process of activation of each neuron is mimicked by means of a weighted sum of the inputs for each ANN node which is then processed via an activation function that eventually generates the node-specific output [190]. The structure characterizing an ANN can be constituted by only one layers of neurons or more, in which case the technique takes the name of "deep learning".

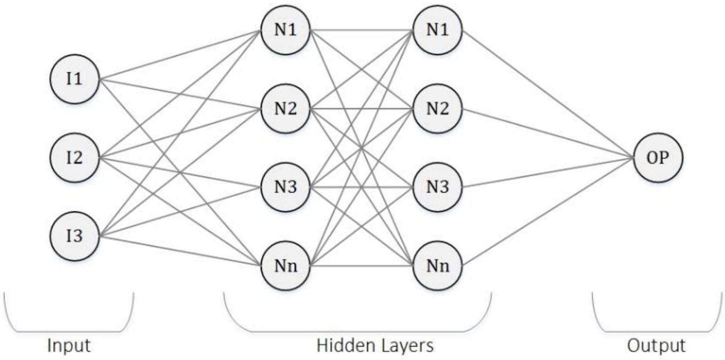


**Figure 2.2** Multi-layer feedforward neural network. I = inputs, Ni = neurons, OP = output. (Adapted from [183]).

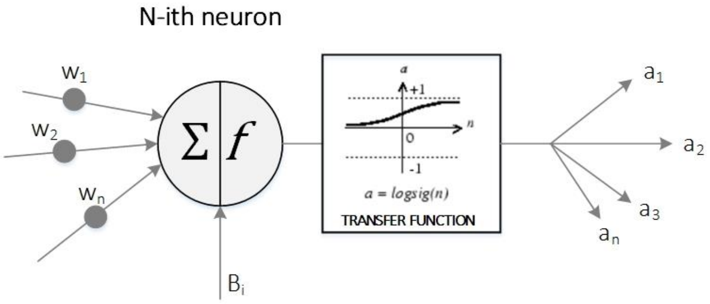


**Figure 2.3:** Generic structure for *N*th neuron. (Adapted from [183, 194]).

Figure 2.2 shows a generic architecture of a multilayer backpropagation shallow neural network with 2 hidden layers, accepting 3 inputs and outputting 1 element. When accessing the neural network architecture the number of layers is provided including also the output layer, therefore in order to fetch the effective hidden layers number it is necessary to subtract one to the overall layers count. A generic neuron representation is provided in Figure 2.3. As it can observed by the figure, each neuron is connected to the others and information exchange happens amongst them. When the information is passed within the same layer it is affected by a bias *Bi*, whereas when it is moved to a different layer it has to be elaborated through a transfer function. Most of the multilayer neural networks adopt log-sigmoid function, whereas ANNs adopted for pattern recognition may utilize tan-sigmoid functions and function fitting problem generally employ linear output neurons [194]. When the information is passed to the neuron and ready to be elaborated, it has to be combined with weights $w_i$, which are calculated during the training phase of the neural network.

### 2.6.2. Genetic algorithms

Genetic algorithms represent a class of evolutionary algorithms employing metaheuristic and natural selection [183] for complex optimisation problems where the selection from a population of individuals (i.e., value) is required as part of the optimization process. The underpinning idea of genetic algorithms is the selection process leading to the determination of the best fit which draws on the principles of natural selection [195]. At the end of each generation, the fittest individual (i.e., array) is selected and passed onto the ensuing one. Its features are then combined with individuals of the new generations in order to gradually improve the overall fit and eventually lead to the convergence of the algorithm.

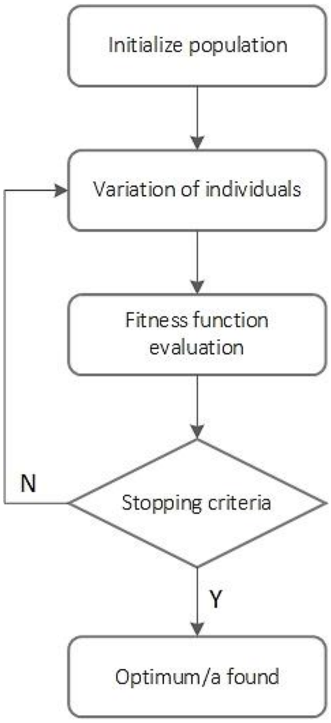


**Figure 2.4:** Basic diagram of the majority of genetic algorithms. (Adapted from [198]).

The origin of genetic algorithms draws on the work by John Holland at the University of Michigan [195–197] in the early 1960s. In his seminal work, Holland explicitly draws upon the concept of natural adaptation, where the best supervisory program (i.e., individual) within a certain population can be considered as successful when able to produce solutions and self-duplicate. Since then, genetic algorithms have been widely applied to a series of domains and their adoption is also popular in conjunction with other evolutionary techniques, hence leading to hybrid combinations [183].

A key advantage of genetic algorithms lies in their nature-based structure, hence in the ability of learning and evolving. The solution is the result of a thorough selection and evolution process across the whole domain of existence of the objective variable, enabling a smoother search for global optimum and not just local ones. This refers to the ability of genetic algorithms to outperform traditional search methods for multi-modal convex problems [198]. Figure 2.4 shows the basic flowchart for the vast majority of evolutionary algorithms which leads to another beneficial aspect of this optimization strategies, namely consisting in their theoretical simplicity. Related to this, genetic algorithms simply require a data structure for the solution's definition, a selection criteria and a performance index to evaluate the solution [198]. As a result, there is no limitation to their applicability in terms of functions' linearity as opposed to other optimization strategies [198]. In fact, as extensively demonstrated in section 2.5, genetic algorithms are also widely integrated with other machine learning techniques, both in terms of neural networks and other evolutionary algorithms.

### 2.6.3. Principal Component Analysis

Principal component (PCA) analysis is a typology of multivariate analysis [167, 199] originally introduced by Pearson [200] in the early 1900s and then further elaborated by Hotelling [201]. The underpinning concept of PCA is that an initial large set of correlated variables $X$ can be reduced to an uncorrelated dataset through the identification of principal components (PC), consisting in a linear combination of the initial set of data [166]. Hence, the vector of the principal components $\boldsymbol{PC}$ can be represented as the linear combination between a transformation matrix $\bar{\bar{T}}$ and the initial dataset matrix $\boldsymbol{X}$.

$$\boldsymbol{PC} = \bar{\bar{T}}\boldsymbol{X}$$

**Equation 3.4:** Definition of Principal Component matrix. [167, 202]

Therefore, PCA is the process of representing a large set of data through its PCs. Namely, the principal components consist in the directions retaining the majority of the information in the context of the dataset [203]. The initial dataset consists in a matrix $\boldsymbol{X}$ of dimensions $u$ x $t$ where the $u$ rows represent the number of observations for the $t$ number of variables. A generic principal component $PC_i$ for the variables $\boldsymbol{X}$ can be defined as in Equation 3.5 based on the eigenvector $\alpha_i$ of the covariance matrix $\Sigma$ corresponding to the largest $i$th eigenvalue $\lambda_i$.

$$PC_i = \alpha_i' \boldsymbol{X}_i$$

**Equation 3.5:** Definition of Principal Component. [167]

The principal components are ordered in a way that the first few are representative of the majority of the variability contained in the initial dataset [167]. Therefore, the first one will retain the highest variance of the whole dataset, the second PC's variance *Var* is second largest but uncorrelated to the first one, and so forth [166]. As an example, the first two PCs can be mathematically expressed an in Equations 3.6 and 3.7, whereas Equation 3.8 expresses the formulation for a generic *k*th PC [166]. As formerly alluded to, the PCs are uncorrelated as the scalar product between the eigenvectors is null and therefore the vectors are orthogonal.

$$PC_1 = \boldsymbol{\alpha}_1' \boldsymbol{X} \qquad \text{with} \qquad Var(PC_1) = \boldsymbol{\alpha}_1' \Sigma \boldsymbol{a}_1 = max_{\|a\|=1} \boldsymbol{\alpha}_1' \Sigma \boldsymbol{a}_1$$

**Equation 3.6:** First Principal Component.

$$PC_2 = \boldsymbol{\alpha}_2' \boldsymbol{X} \quad \text{where} \quad Var(PC_2) = \boldsymbol{\alpha}_2' \Sigma \boldsymbol{a}_2 = max_{\|a\|=1} \boldsymbol{\alpha}_2' \Sigma \boldsymbol{a}_2 \quad \text{and} \quad \boldsymbol{\alpha}_1' \Sigma \boldsymbol{a}_2 = 0$$

**Equation 3.7:** Second Principal Component.

$$PC_k = \boldsymbol{\alpha}_k' \boldsymbol{X} \qquad \text{where} \qquad Var(PC_k) = \boldsymbol{\alpha}_k' \Sigma \boldsymbol{a}_k = max_{\|a\|=1} \boldsymbol{\alpha}_k' \Sigma \boldsymbol{a}_k$$
$$\text{and} \quad \boldsymbol{\alpha}_k' \Sigma \boldsymbol{a}_p = 0, \;\; p = 1, \dots, k-1$$

**Equation 3.8:** Generic *k*th Principal Component.

After calculating the PCs, the problem of how many of them to retain is posed. The need of neglecting some of the PCs stems from the intention of reducing the initial set of $t$ variables with the first $p$ PCs, where ideally $p < t$. The literature proposes a great deal of methodologies [167], such as:

- Cumulative percentage of total variation;
- Sizes of variances of the PCs;
- Scree Graph and Log-Eigenvalue Diagram; and
- Number of PCs with unequal eigenvalues.

However, the proposed list does not represent an exhaustive review of all the possible techniques, but only of the main ones. The first approach consists in evaluating the cumulative percentage of variance for all the PCs after having established a threshold for an acceptable total percentage of variation which is considered a reliable representation of the initial dataset (e.g., 90%) [167]. As demonstrated in Equation 3.9, the final percentage of variance $TVp$ for the $p$ PCs accounting for a variability of $p$ variables in the initial dataset is given by the cumulative summation of the variance $var_i$ for each PC.

$$TV_p = \frac{100}{t}\sum_{i=1}^{i=p} var_i$$

**Equation 3.8:** Percentage of dataset (i.e., total variance) *TVp* represented by the *p* PCs (*TVp*) which account for the variability of the *p* variables in the initial dataset.

However, this methodology can be adopted only when the covariance matrix Σ is adopted. As an alternative, the size of the PCs can be evaluated. This stems from the concept that in absence of a covariance matrix, PCs with a variance inferior to 1 are not as informative as ones showing variances exceeding the unit value. Therefore, this rule suggests to retain only the PCs exhibiting a variance larger than 1. Another methodology than can be employed consists in the scree graph, which however entails a certain degree of uncertainty due to high subjectivity implied by this strategy. The scree graph is the plot of the PCs' variances $var_i$ against the index $i$ [167, 204, 205]. Namely, the number $p$ of PCs to be retained is identified in correspondence of a so-called "elbow" in the plot. Cattell's scree plot [204] is usually featured by a regular decrease in the eigenvalues until a large difference which is then followed by variances discrepancies of 0.1 or even smaller [205]. The number of PCs to be retained coincides with the number immediately preceding the largest change in variance.

Principal components analysis is recognised to be an established methodology for data reduction even though for engineering applications a potential drawback could be identified in the lack of physical meaning of the PCs. As a result, it is not possible from the PCs to refer back to the initial set of variables $\boldsymbol{X}$ unless adopting the transformation matrix $\bar{\bar{T}}$ and reversing the linear transformation as explained at the beginning of this section. However, this strategy is acknowledged by the literature as perhaps one of the most established even though more refined analyses could consider the employment of nonlinear techniques.

### 2.6.4. Summary

This section brought the focus on the techniques identified in section 2.5, investigating more in detail the underpinning theoretical aspects. The analysis evidences how backpropagation neural networks are easy to develop and to implement. In fact, most of the research reviewed in section 2.5 utilized the MATLAB machine learning toolbox, which proves its efficacy and results provision quality.

Similarly, genetic algorithms appear to be advantageous given their ability of finding the global optimum especially in convex problems outperforming traditional algorithms which instead tend to limit the search to local optimums. Research also demonstrated how GAs adopt a straightforward flow of tasks which provides them with theoretical simplicity that constitutes a major advantage for their application. Additionally, the opportunity for integration to both linear and nonlinear problems represents benefit the proposed research, given the complex interrelations between the variables entailed by a structural analysis in relation to a building system.

As far as PCA algorithm is concerned, the proposed review highlighted how the theoretical background exhibits the potential for integration with machine learning techniques. However, the data transformed into the PCs lose their physical meaning, requiring to systematically operate the transformation utilizing the covariance matrix. Despite that, the PCA approach has been established in research to provide reliable results by the adoption of the cumulative percentage of total variation through the PCs analysis, which is therefore the choice for this research.

## 2.7. Seismic-induced structural mechanisms on reinforced concrete infilled frames

In order to lay the foundation for the ensuing investigations, it is necessary to identify the failure mechanisms which are most frequently registered in infilled RC frames. The current research focusses in fact on RC buildings given their prevalence in the context of the existing building stock. To do so, a series of significant seismic events were analysed in terms of damages to buildings and relevant research was examined to outline the most common underlying faults. Namely, earthquakes in Italy (i.e., L'Aquila 2009 and Emilia 2012), Turkey (i.e., August and November 1999, 2011 Van earthquakes), Peru (i.e., Pisco 2007), Ecuador (i.e., Muisne 2016) and China (i.e., Wenchuan 2008) were accounted in this review phase.

Tables 2.7 and 2.8 respectively provide an overview of the most common faults and failures typologies identified in the aftermath of the above mentioned seismic events. As far as Table 2.4 is concerned, the faults have been divided into two main categories, namely physical and human factors. Physical factors relate to the building itself and to its features in terms of materials, geometry and specificities. These features have been further grouped into two subsets according to their level of recurrence over the whole building.

**Table 2.7**: Summary of most common faults for seismic failure of RC structures.

| **PHYSICAL FACTORS** |
|---|
| **Global criticalities** |
| Non coincidence between centre of mass and structural centre [206, 207] |
| Shape irregularities (in-plan, in-height) [154, 156, 206, 208, 209] |
| Short-columns (e.g., partial infill with strip window) [154, 206, 210] |
| Poor concrete mixture [155, 157, 206, 208] |
| Inadequate floor beam depth [206] |
| Excessive dislocation [206] |
| **Local criticalities** |
| Poor connection between masonry infills and ring beam or concrete frame [155, 211] |
| Stiff beam-weak column connection [157, 206] |
| Poor structural detailing (e.g., reinforcement in correspondence of connections, insufficient concrete cover) [154–157, 206–209] |
| Deficiencies in masonry infills (e.g., poor connection between different wythes of masonry infills) [154–157] |
| Under dimensioning of seismic joints [157, 207] |
| **HUMAN/PROCESS FACTORS _ Non-quantifiable factors** |
| Level of capacity design rules [114] |
| Mistakes in the construction phase [206] |
| Wrong application of architectural and/or structural projects [206] |
| Insufficient or absent geotechnical site analysis [44, 157, 206] |
| Wrong site selection [157, 206] |
| Inadequacy of building code [206] |
| Unsuitable preparation of professional figures involved in the design process [206] |
| Non-compliance to building regulations [206] |
| Unsupervised construction [206] |
| Poor workmanship [154, 206] |
| Variations during construction [157] |
| Maintenance/ state of conservation [154] |

**Table 2.8:** Summary of most common failures on RC buildings.

| **STRUCTURAL DAMAGES** |
|---|
| Damages to beam-columns connections [154, 156] |
| Soft-storey behaviour [44, 154, 211–214, 155–157, 206–210] |
| Damage of short columns [154, 210, 212] |
| Development of plastic hinges [207, 210] |
| Pounding between adjacent buildings [207, 210, 212] |
| **NON-STRUCTURAL DAMAGES** |
| Cracking and/or out-of-plane collapse of masonry walls [154, 156, 207–210, 212] |
| Partition walls damages [208–210, 215] |

As an example, concrete mixture is accounted as a global feature whereas the design of seismic joints is considered as a local criticality. Local factors required a more detailed calculation, specific to the portion of the building they refer to and pertaining a further stage of the design compared to the one involving the global factors. Human-related faults include instead all those unquantifiable factors that affect negatively the construction prior to the seismic event, including for instance a poor site choice or the lack of proper geotechnical investigations.

Overall, the classified damage typologies were very similar despite potentially country-specific influences in terms of materials or building codes. However, the main failure modes registered were soft-storey behaviours and non-structural damages to masonry infills, as it can be deduced from Table 2.5. Based on the damage classification to RC structures following to the 1999 earthquake in Turkey provided by Ercüment [206], several similarities can be found with the ones undergone by the buildings in the city of Old Beichuan [44, 214], as it will be explained more in detail in the following paragraphs. Another factor that has to be accounted while surveying a building consists in the geometric regularity, both in-plan and in-height which acquires particular relevance when it comes to dynamic conditions, and as showed during L’Aquila in 2009 [154] and in Turkey in 1999 [206].

Perhaps masonry infills consisted in the main feature that all the analysed reports have pointed out to be the most vulnerable and hence amongst the first ones to undergo damage. Specifically in the case of the 2009 seismic event in L’Aquila, the main cause of failure for RC buildings was in fact identified in the damage undergone by masonry infills [156, 207] and similarly has been registered regarding the 2012 earthquake in Emilia [215]. To this regard, Braga et al. [216] investigated the behavior of non-structural features in the context of RC structures in the 2009 L’Aquila earthquake, examining different types of infill and their seismic performance. Rosti et al. [215] provide instead a detailed insight of the different damage typologies registered during the L’Aquila seismic event of 2009 in Italy. The authors differentiate the damaged portions of the buildings according to the classification provided by the AeDES survey forms for post-disaster damage assessment. Analogously, in the Peruvian seismic event of 2007 in Pisco the most common failure registered for RC buildings was related to cracking or expulsion of masonry infills from the concrete frame [212].

Masonry infills are generally classified as non-structural elements in the context of a RC structure. However, their role in absorbing horizontal actions and contributing to the overall dynamic performance and rigidity of the building has been widely studied and proved by a great deal of researches [215–219]. Damage to masonry infills hinders the functionality of the building, causing also financial and human losses [215]. Three main failure typologies can be accounted, namely (i) dislocation of the central portion of the panel, (ii) diagonal cracking due to shear action, (iii) crashing of corner portions of the panel [156].

In other cases the panel can be completely expelled by the main concrete frame [154, 206]. As highlighted by Ricci et al. [156], the interaction between masonry infills and RC frame has a twofold implication, being both global and local. As a local effect, an excessive concentration of shear in columns [156] occurs when short-columns are created by partial infilled walls, such in the case of strip windows. On the other hand, an irregular distribution of masonry infills can lead to global effects such as the soft-storey phenomenon.

Soft-storey behavior has to be mentioned as it is accounted amongst one of the main failure modes for RC frames. This strategy entails the limitation of infills at the ground level creating in-height irregularities and significant stiffness and inertia variations between the upper body and lowest floor. This phenomenon was registered in several countries, namely Italy [154, 156], Turkey [157, 206], Ecuador [155] and China [44, 213, 214]. However, soft-storey does not have to be mistaken with storey-crushing. While the latter is often caused by shear-induced, brittle failure of columns, [209] soft-storey entails the development of plastic hinges often in correspondence of the frame’s nodes or in discontinuity points.

As far as the concrete mixture is concerned, a clarification has to be pinpointed. Field investigations can provide meaningful insights in relation to the distribution of the aggregates and their nature (i.e., diameter and typology). Additionally, on-site inspections can help characterize the quality of the cement, as in the case of the L’Aquila seismic event [220]. Although, the specific concrete class cannot be surveyed from field investigations other than collecting samples and testing them over laboratory tests. However, samples’ collection has to be carefully planned in order not to further endanger the structural stability.

Steel reinforcement plays a primary role in the seismic behaviour of a structure, compensating for the lack of traction that the concrete is unable to withstand and improving the overall ductility. A clear distinction has to be mentioned in relation to buildings’ damage due to smooth rebar and faults linked to wrong calculation of ribbed rebar. This particularly applies to contexts such as Italy [154] and Turkey [157], as opposed to what registered in the aftermath of the Wenchuan earthquake in terms of damage.

While in Italy and Turkey several damaged structures had been erected in accordance to past prescriptions with less seismic awareness (e.g., RD2229/39 in Italy) [216], in China the explored areas included buildings with already ribbed bars in place, at least in the surveyed area of Old Beichuan. This leads clearly to ascribe the damage not to the nature of the reinforcement adopted (i.e., smooth or ribbed), but rather to perhaps an inadequacy of the building codes or to an incorrect application of those.

As shown in Table 2.4 there are as many human-related factors as technical ones and this results in a great deal of elements that cannot be taken into account into a structural model. These factors apply to pre-construction processes (e.g., site selection, geotechnical investigations), but also to faults associated to the construction process such as low quality workmanship or undocumented changes in the design [157]. Although not directly quantifiable, these factors significantly affect the final performance of the structure as it was investigated by Bayraktar et al. [157].

The authors classified 90 RC buildings' performances in the aftermath of the 2011 Van earthquake in Turkey, taking into account different features, amongst which also the correspondence between the buildings' state of the art and the documented design. The analysis uncovered that 57% of the structures were discordant from the structural design documentation, while just 3% showed a correspondence and for the remaining 40% no documentation was available.

Calvi [114] emphasized the importance of understanding which design strategy has been employed in a particular building, using as a guidance the year of construction to deduce the enforcing regulations. This can highlight whether capacity design has been adopted or not and therefore informing the model employed to simulate the building's behaviour.

Several building regulations nowadays take into consideration the quality and quantity of the information when it is required to tackle structural-related matters for existing buildings [33, 106]. The Eurocodes [106] propose Knowledge Levels (KL) to which Confidence Factors (CF) are associated according to attained accuracy in terms of documentation and in-situ surveys.

The CF is functional to reduce resistances and structural capacities to account for the level of uncertainty linked to a scarce knowledge of the building. This is functional to inform reconstruction or repair processes on existing buildings. In a situation such as the one in Old Beichuan, no documentation (e.g., calculations or drawings) was available and the access to the structure was limited given the significant damage undergone by the building.

To this regard, Italian building regulations [33] prescribe the calculation of a simulated design while attaining the lowest level of knowledge [218]. Namely, the simulated design is carried out adopting the regulations in effect at the time of the construction and this methodology enables to gather all the information regarding reinforcement and structural detailing otherwise unavailable. This methodology can therefore speed up this process and find the effective real values of the unknown parameters, taking into account potential changes that might have occurred over time and of which no physical documentation is available or not matching the state of the art [157]. The value found throughout this methodology is then the closest to the realistic state of the art at the time of the disruption.

Taking into account the analysis provided by Braga et al. [216] it is possible to find a correspondence with the structures in Figure 2.5. Referring in detail to the case of Old Beichuan, a significant adoption of a poor concrete mixture was identified in coincidence with an unsuitable reinforcement detailing of the section, as it can be acknowledged in Figure 2.(c). The section appears insufficiently reinforced longitudinally and the bar diameter appears too exiguous [44]. Similarly, shear reinforcement appears not present in sufficient amount. As a consequence of these factors the section underwent a clear brittle failure. This factor coincides also with what identified in Table 2.5 as a global factor and in relation to the previously reviewed reports.

Several buildings experienced soft-storey collapse as a consequence of an irregular distribution of masonry elements throughout the layout of the building [44, 214] and this was intensified by the pounding with adjacent buildings in some cases, such as the one in Figure 2. (g).

Similarly, in Figure 2. (a), (d) and (f) a soft-storey mechanism is displayed, but it is also evident the diagonal cracking of the masonry infills probably due to shear and internal stress in the infill itself. Figure 2.5 (e) shows instead a rather good behavior of the RC frame while the masonry exhibits out-of-plane collapse perhaps due to an insufficient connection to the frame. In addition to that, external claddings are usually an unsafe design choice in seismic prone areas as their unsuitable connection can result in consistent hazard in case of their detachment from the wall.

Figure 2.5 (b) shows instead a soft-storey mechanism at the first floor with the development of plastic hinges in coincidence of the connection beams-column in the south-eastern corner of the building. Another relevant example that can be provided to support this statement is the case of Beichuan Hotel in Old Beichuan, as shown in Figure 2.(h). Namely, the discontinuity of the shear wall at the ground floor caused a sudden change in the structural stiffness, inducing the energy release in the upper storeys, not provided with shear walls at all. The combination of this element to the strip windows at the upper floors and the consequent short columns created by the partial infills led to a higher dislocation of the frame in coincidence with the node between the second and third floors.

(a) (b)

(c) (d)

(e) (f)

(g) (h)

**Figure 2.5*:*** Examples of seismic failure of RC buildings in Old Beichuan due to the 2008 Wenchuan earthquake. (a) Soft-storey behavior (b) Torsional dislocation (c) poor concrete mixture and reinforcement detailing (d) diagonal shear crack on masonry infill and soft-storey collapse of the structure (e) out-of-plane failure of masonry infills poorly connected to the frame (f) soft-storey collapse and diagonal shear cracks on masonry infills (g) soft-storey mechanism and lateral pounding with adjacent buildings (h) shear-walls in-height discontinuity.

Prior to more in depth insights, it is necessary to highlight some assumptions and considerations at the base of the methodology. In first instance, this case study application entailed a linear dynamic structural analysis (i.e., modal analysis) [106], albeit being applicable to any other typology. On a different note, it is not possible to input reinforcement information in the model prior to the calculation process. In fact, reinforcement calculation can only be introduced as a result of the overall concrete structural analysis, evaluating the necessary rebar for each section. Nevertheless, it would be fruitful to investigate the potential of implementation in Robot of older building regulations in order to be able to replicate and verify existing structures with respect to the building code according to they had been designed.

## 2.8. Masonry-infills characterization for semantic modelling

Section 2.7 provided an extensive overview of the most common structural failures in masonry infilled RC buildings, highlighting that one of the most vulnerable elements consist in masonry infills. Namely, their primary function is to ensure stability in case of seismic actions, limiting the excessive deformability of the frame. Building upon these considerations and adopting a forward-looking approach in preparation for a case-study building modelling, this section will explore and investigate how masonry infills can be analytically characterized to be integrated into a structural semantic building model.

The task of converting masonry infill panels into equivalent structural elements derives from the need of aiding the computational tasks when assessing the performance of a building and attaining an accurate digital representation of the structure. Despite the rich and flourishing body of research concerning this domain, a review of pertinent literature [217, 221] highlighted two main strategies for the modelling of masonry infill walls, namely consisting in micro and macro-modelling.

### 2.8.1. Micro-modelling strategies for masonry infill panels

Micro-model methodologies ground on the local interaction between the concrete frame and the masonry panel [217, 221], often involving finite elements modelling (FEM) in order to simulate the sliding of masonry elements and cracking of concrete. Given their consistent level of complexity, micro-modelling is often adopted to assess local effects rather than being applied on the whole building structure. When dealing with existing structures the characterization of building features (e.g., material mechanical properties, frame sections) is often knotty in the occurrence of lack of relevant documentation. On the other side, micro-modelling of masonry infills might involve featuring plastic hinges in the frame to account for the plasticity of the structure after the ultimate limit state [221, 222]. In addition, frame nodes are often modelled as rigid links [221, 222] and the strut itself should be characterized not linearly as described in the context of the macro-models, but by devising a force-displacement relationship such as carried out by Cavalieri and Trapani [221]. However, for the purposes of this analysis linear dynamic analysis will be performed, hence the plastic capacity is not investigated as it would be done instead while adopting a pushover analysis method. The structure's behavior remains hence in the elastic phase. In addition to that, plastic hinges placed in the different parts of the frame need to be characterized grounding on the RC in that particular section, consisting in a very unreliable task when detailed information are not available.

### 2.8.2. Macro-modelling strategies for masonry infill panels

Macro-models require the replacement of the masonry infill panel with strut elements pinned at the extremities to the frame node, as showed in Figure 2.6. This modelling technique allows to factor in the stiffening contribution provided by the masonry infills but not their induced load on the underlying beam, hence the struts have to be realized by means of compression-only elements featured by no weight. As stated by FEMA 356 in fact, "the equivalent strut shall have the same thickness and modulus of elasticity as the infill panel it represents"[107].

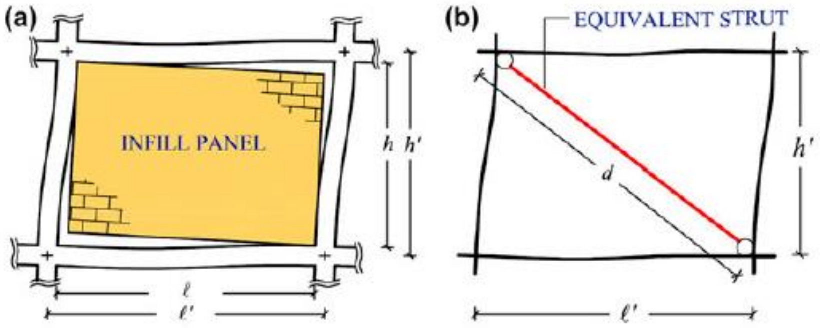


**Figure 2.6:** Macromodel methodology for masonry infill in RC structures [217]

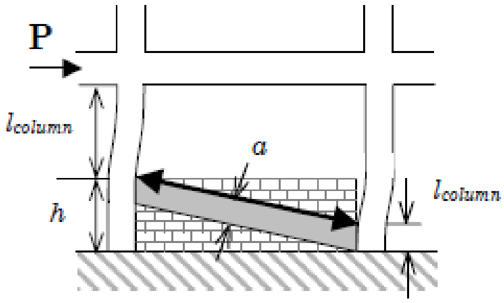


**Figure 2.7:** Partially infilled RC frame and equivalent strut [source: [222]].

The most relevant advantages of this approach consist in its practical applicability given the ease of implementation and calculation of the strut itself. Other authors, such as Al-Chaar [222], also adapt the model for partly infilled masonry walls, as in

Figure 2.7 but also including the occurrence of window presence. The calculation of the struts' geometrical properties which is mostly employed nowadays has been devised by Stafford Smith [223] and then adopted in ensuing works and regulatory frameworks [107, 222, 224]. Namely, Stafford Smith seminal work grounded on the similarity of the interaction masonry infill-frame with a Winkler foundation beam on elastic ground [223, 225, 226].

Macro-modelling techniques particularly benefit global structural assessments as opposed to local analyses where a single panel is considered. Namely, when the global behaviour of the structure is prioritized over local effects for the purpose of a specific analysis, it is not practical to over-complicate the model by finite elements modelling of masonry infills. This would in fact result in cumbersome computational efforts and not proportionate advantages in terms of results, whereas the adoption of struts provides a reliable simulation of masonry infills simplifying both calculation and modelling [227]. Most literature [217, 223, 228–231] analyses the struts positioned just in one direction, while in case of dynamic analysis they are usually oriented according to the direction of the maximum demand, such in the study proposed by Fiore [232]. Conversely, Dolce [227] recommends to implement them in two directions forming a St. Andrew's cross when dealing with dynamic analysis while the one-direction model can still be considered for static analysis.

With respect to partially infilled walls, which is the case of the analysed building, the literature is less rich and mainly empirical, as highlighted by Pradhan et al. [230]. Generally in new constructions this typology of infill is not recommended given the increase of shear solicitations occurring in correspondence of the free length column and the infilled frame portion, especially in presence of horizontal actions. Partially infills also reduce the contact surface between masonry and columns, leading to short-columns phenomena caused by an increased rigidity of the resulting structural elements. In fact, rigidity is inversely proportionate to the square of the element's length.

### 2.8.3. Summary

Section 2.8 focused on investigating existing approaches for parametric structural characterization of masonry infill panels. Research evidenced how the most effective strategy in case of seismic actions consists in adopting a two-directional St. Andrew cross adopting compression-only strut elements. The latter are in fact able to effectively characterize the stiffness provided by the masonry to the frame, and the 2-direction orientation advantages dynamic analysis given the uncertainty regarding the major direction of acceleration.

With respect to the algorithmic formulation, Stafford-Smith's seminal work is still nowadays the most established formulation for strut calculation. This does not apply for analyses at the local level (i.e., micro-models) where a much higher level of detail has to be employed, however for the purpose of this research a characterization based on mechanical properties and infills geometry satisfies the objectives.

## 2.9. Discussion and identification of Research Gaps

Based on the findings provided by the proposed extensive review, two macro-categories are identified to pursue resilience assessment of buildings in face of geo-environmental hazards, namely qualitative and quantitative approaches. Quantitative approaches provide a focussed but scattered perspective and despite the higher accuracy there is a significant disagreement in the way resilience has to be approached. Conversely, qualitative strategies show a more uniform trend in the general characterization of resilience and its assessment adopting managerial and organizational approaches. Despite that, qualitative approaches are not scalable and the subjectivity involved in the assessments leads to the impossibility of considering them as the only applicable strategy. Qualitative strategies, in the attempt of being "holistic" tend to misinterpret this concept applying it to a variety of hazards and objectives (i.e., buildings, infrastructures and people) hence resulting in granular approaches. In order to answer the questions of "resilience of what? Resilience to what?" the identification of a specific object and a set of well-defined hazards is necessary. A holistic approach is therefore not one that attempts to include as many variables as possible, but one able to target the meaningful stressors and vulnerable features related to the object of the analysis. A meaningful gap is therefore highlighted in relation to the disconnection between the two scales, which contradicts what recent trends for resilience demand for, namely comprehensive and applicable approaches.

At the building-scale, resilience is instead quantified adopting analytical approaches and in most cases involving structural behaviour analyses. However, some research exhibited the adoption of semi-qualitative methodologies for resilience assessment, namely expert-based approaches. These recall the structure of qualitative resilience management strategies where a set of criteria are identified and scored, entailing a significant level of uncertainty but proving their applicability for quick damage appraisals. However, performance-based approaches proved to be more established and authoritative for the scope of building-scale resilience and reliability structural assessment, also due to their high interconnectivity with regulatory frameworks.

Following to the established adoption of performance-based approaches, it is determined that displacement represents the best flag for the overall building's ductility in dynamic conditions. However, research and regulatory frameworks do not exhibit significant agreement in relation to a univocal EDP choice, leading to the identification of the two most authoritative, namely node displacement and IDR. In terms of damage assessment, the review highlighted that qualitative damage scales can provide a significant contribution, although their utilization should be limited to those cases where a less analytical approach is expected. To this respect, it is observed how these strategy could represent an intermediate step between building-level (i.e., micro) and district-scale (i.e., macro) approaches given their high potential for integration and extrapolation when scaling up the area of analysis.

Related work in seismic engineering significantly highlights the strong deployment of machine learning and AI techniques at the building-level, which is representing a fertile domain of research and exhibiting a strong tendency towards the automation of systematic tasks. The review of AI-augmented structural analyses demonstrated a significant application of neural networks and evolutionary algorithm both in structural and architectural domains. However, in very few instances the optimization and design tasks are performed together in conjunction with the adoption of commercial software, especially for what concerns structural analysis. As demonstrated by the review, the architectural field shows a more organic tendency to integrate parametric software to optimization tasks with the use of Grasshopper and Rhino. On the contrary, the structural field outside the academic environment appears to be reluctant to adopt machine learning techniques, remaining attached to traditional approaches. Some of the approaches analysed during the review appeared to have adopted structural software (e.g., SAP2000) and then performed optimizations tasks, however the two remained disjointed. Conversely, the architectural domain has managed to pursue a higher interconnectivity amongst the optimization and the software, perhaps thanks to the contribution of Grasshopper and Galapagos which is probably more utilized than Karamba (i.e., structural optimization tool, plugin for Grasshopper) by structural engineer.

Additionally, with respect to existing optimization tools for structural optimization, such as Karamba or SmartSizer, the strategy employed is merely in terms of topology and size. Specifically, Karamba adopts a genetic algorithms and a drawback was highlighted in this respect and namely regarding the simulation time. As a result, there is a consistent need to decentralize the optimization from the structural design software. This stems from the high discrepancy in terms of efficiency which is registered between the software itself and the GA, where the latter's performance is often hindered by the lower simulation time of the software. Although this issue could be partially solved by increasing the computational power (i.e., processor power, RAM), it is argued that cost-wise it is more convenient to introduce a leaner optimization and design strategy which would reduce systematic and computationally burdensome tasks.

On a different note, the body of knowledge in terms of research is rich of successful applications of machine learning techniques to structural design, even though these are often limited to one task, whether it is performance or damage assessment, optimization or design. As a result, there is a tendency to extreme detail when dealing with building-scale analyses and symmetrically, district-level approaches tend to generalize and lose focus. At the same time, most building-scale approaches do not question regulatory frameworks, even though lessons learnt demonstrate that sometimes building regulations prove to be ineffective even though compliance was attained.

From a district-level perspective the review highlighted how the current research could benefit from the adoption of a Delphi-based expert consultation with the aim of validating the proposed resilience indicators. As explained in the review, the advantages of this approach lie in the full anonymity amongst the experts and the opportunity of gathering feedback from a global and multi-disciplinary research and industrial community.

In light of the above, it appears evident how two main research gaps can be found which would also coincide with the main research threads:

- Disconnection amongst micro and macro resilience management approaches (i.e., qualitative approach);
- Integration of optimization strategies to commercial tools adopting machine learning techniques for damage assessment and prediction (i.e., quantitative approach).

## 2.10. Conclusion

This chapter is aimed at investigating modern approaches to structural analysis and resilience management in a comprehensive way and hence respectively addressing analytical (i.e., quantitative) and qualitative strategies. The review mainly highlighted a global disconnection amongst the two approaches, contrasting with current theoretical views and demands for resilience requiring scalable and comprehensive approaches. Similarly, it was demonstrated how structural engineering is behind other domains (e.g., architecture) for what pertains the adoption of augmented computational strategies to enhance traditional approaches. However, some successful attempts are attained, even though their adoption is still limited in common engineering practice.

In addition to the above, the presented body of knowledge evidenced how research approaches provide successful integrations of traditional engineering and machine learning applications demonstrating how the latter can concretely enhance standard techniques. The reviewed literature proves how evolutionary computing and neural networks are the most successfully implemented, namely for damage assessment and predictions. Whereas the integration of GAs and ANNs is mainly adopted for vibration analysis, GA alone are utilized for structural optimization. However, these two techniques are also enhanced by the adoption of dimensionality reduction strategies which significantly smooth the transition between GA and ANNs training by establishing correlations amongst the dataset variables and hence eliminating redundancies in the dataset.

The literature review presented also highlighted how, amongst dimensionality reduction strategies, Principal Component Analysis (PCA) represents a well-established methodology. The advantages of such strategy stem from the relatively simple underpinning algorithms and the capacity of providing a reliable representation of the dataset, as extensively proven by applications presented in relation to the existing literature.

Overall, Chapter 2 outlined the current state-of the-art in relation to resilience from both a disaster-management and structural characterization perspective, identifying meaningful gaps which represent a valid research opportunity for this work. Stemming from the considerations provided herein, Chapter 3 will delineate the methodology adopted to undertake the research.

# 3. Methodology

Chapter 2 identified two main disaster resilience threads, namely qualitative (i.e., macro-scale) and quantitative (i.e., micro-level). It also provided an overview in relation to the state-of-the-art of machine learning techniques applied to structural engineering and seismic analyses with respect to buildings, but it also encompassed resilience management strategies at the district-level. This Chapter will instead delineate how the techniques identified in the Literature Review are adopted and deployed. Namely, the qualitative resilience management framework will benefit from a Delphi-based expert consultation, whereas the building-level approach adopts Artificial Neural Networks, Genetic Algorithms and Principal Component Analysis. A detailed description of how the research questions are addressed is provided in the context of the pertinent contribution.

## 3.1. Philosophical stance and Research methodologies

The choice of a specific research methodology stems from the preliminary identification of the underpinning theoretical drivers and epistemological approaches, which are generally derived from a philosophical background and are functional to answer the question of “why research?” [233]. This section will therefore adopt a top-down approach in identifying a suitable theoretical driver for this research and the consequential methodology functional to guide the research work.

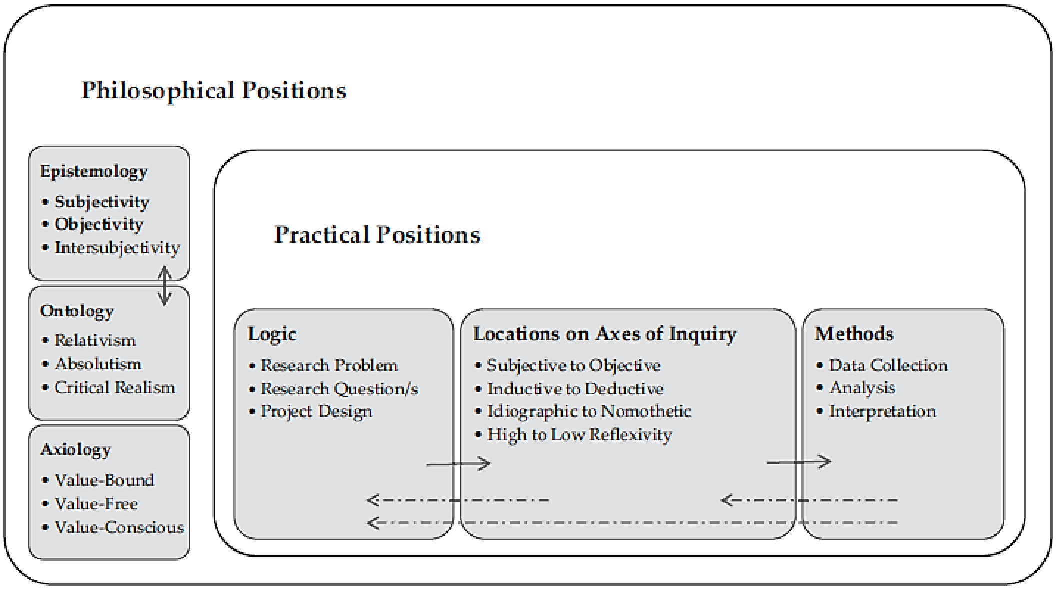


**Figure 3.1:** Interrelation between philosophical stances and research methods [234].

Firstly, the choice of an epistemological stance is motivated by its definition, concerning the definition of knowledge creation itself which is also what research is about [233, 234]. Grounding on the literature review and the identification of two main research threads coinciding with a qualitative and a quantitative methodology, the correspondence to respectively objectivism and subjectivism as philosophical paradigms is immediate [233]. Whereas objectivism adopts an analytical and practical approach towards the interpretation of scientific facts and data, subjectivism entails a phenomenological stance and a qualitative research methodology. Within the scope of this research both of them are functional to achieve a good understanding of resilience, being it a complex concept requiring an interdisciplinary approach.

As a result, the consequential adoption of both qualitative and quantitative research methodologies [235] is justified by the main research threads identified over the literature review. However, while the building-scale approach would be featured by a merely quantitative approach, the district-level research methodology requires further considerations. Namely, having stated in the literature review the intention of adopting a Delphi-based consultation and considering the statistical analyses required to further perform data-processing, it would be incorrect to categorize this methodology as merely qualitative. In fact, qualitative research methodologies are generally classified as coinciding with the adoption of a purely non-numerical dataset [233, 235]. In light of the above it can be concluded that while the building-scale approach is featured by an objectivist philosophical stance and a quantitative research methodology, the district-scale instead adopts a mixed position [234]. Its featuring research stance cannot be just categorized either as subjectivist or objectivist and similarly can be observed with respect to the research methodology.

## 3.2. Conceptual framework for built environment resilience

This section presents the conceptualization of resilience adopted for this research as well as a mathematical formulation to endorse it. The key elements of the formerly presented review on resilience are factored into the framework and the adopted overall research methodology is presented adopting a top-down approach. Therefore, this section will gradually scale down from the overall framework to the key components and objectives to which resilience is addressed. A higher prominence is given to qualitative and quantitative approaches aimed at enhancing and assessing resilience in face of geo-environmental hazards, as presented in the review section. The proposed research aims then at reducing the vulnerability, hence increasing the resiliency level, of buildings in face of seismic hazards. Building-scale quantitative assessments will inform the urban-scale qualitative framework in order to combine the two scales of analysis.

In order to clarify the terminology adopted henceforth, a concise glossary is provided:

- Built Environment (BE) Intrinsic Features: Comprises the totality of structural and non-structural features for the built environment, including the status variables throughout the lifespan;
- Geo-Environmental Hazard: Includes both natural and human-induced hazards (e.g., seismic and volcanic activity, landslide, floods) potentially leading to physical or human losses;
- Geo-Environmental Disaster: The consequence of a hazardous event or combination of them which were not effectively mitigated and eventually led to a loss of functionality in the community;
- Built Environment Resilience: The ability of the built environment to proactively react and evolve in face of hazardous exogenous events (e.g., earthquakes, landslides) eventually attaining a new stability performance level;
- Built Environment Vulnerability: it represents the extent to which the built environment can be potentially damaged by a Geo-Environmental Hazard.
- Built Environment Risk: the degree of exposure of the built environment to a specific Hazard in relation.

Figure 3.2 outlines the proposed framework which captures the main concepts highlighted by the review chapter. The methodology is interdisciplinary given its generic nature and also in terms of stressors acting on the built environment. Nonetheless, given the focus of the presented research, its adoption for resilience assessment in face of geo-environmental hazards is presented.

The built-environment characteristics identify both the structural and non-structural components that physically constitute the built environment system and its elements. In terms of structural features, this would entail the consideration of the material (i.e., wooden, steel, reinforced concrete, masonry) and the strategy (e.g., frame, load-bearing walls), whereas non-structural components include for instance HVAC, electrical and plumbing systems. Additional features to consider consist in foundation type, construction age and maintenance strategies that would also contribute to resilience.

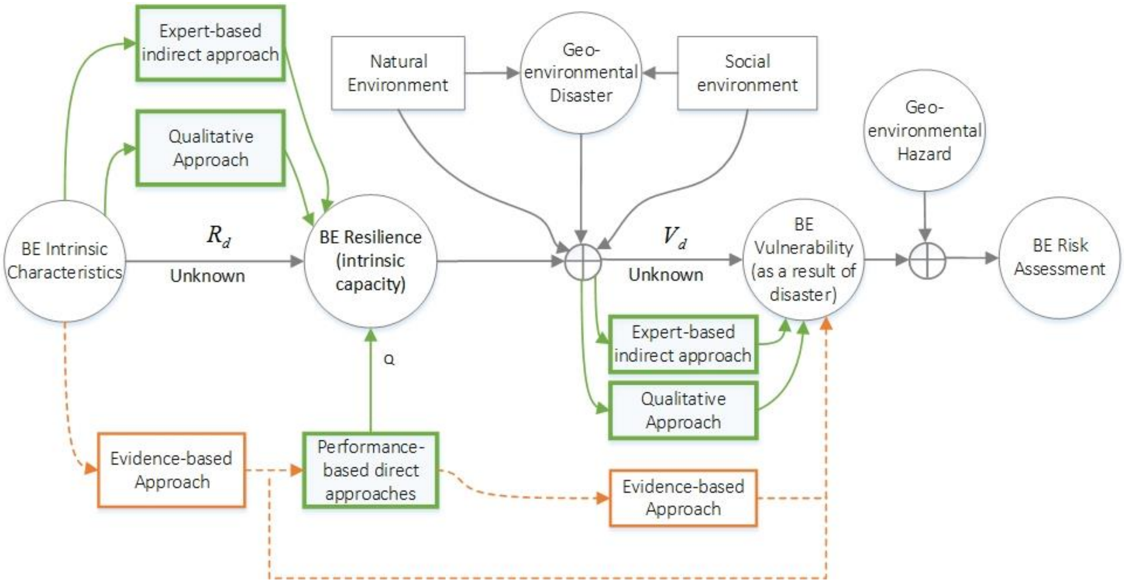


**Figure 3.2:** Conceptual framework for the resilience of the built environment [43].

As mentioned previously in the review section, resilience has to be object and hazard-specific (i.e., resilience of what and resilience to what) [42], therefore when defining resilience the hazard has to be coupled to its “target object”. As an example, a construction can be earthquake-resilient, flood-resilient, landslide-resilience or all the above. When instead resilience is generally approached, the hazard is generic and it could be any geo-environmental event. The proposed generic formulation of resilience is presented in Equation 3.1, where $R_d$ represents the function of resilience in relation to a specific hazardous event $T$. A represents the construction age, *F* is the foundation technique (e.g., piles, plinths or slab foundation), while $S_c$ and $N_c$ stand for structural and non-structural components. Similarly, $S_s$ and $N_s$ represent the regulatory frameworks and statutes adopted for the design, operation and maintenance of structural and non-structural components, while $U_r$ is an unquantified uncertainty of the model in terms of resilience.

$$Resilience = R_d(T, A, F, S_c, S_s, N_c, N_s, U_r)$$

**Equation 3.1:** Generic formulation of resilience [43].

A detailed classification of both structural and non-structural components is proposed by NEHRP seismic provisions [236] where standards for structural and non-structural components are listed. As an example, emergency lighting has to be designed, operated and maintained in a way such to allow a proper functioning in the aftermath of a seismic event. More generally, non-structural components contributing to the performance of critical infrastructures have to be guaranteed as functioning in the occurrence of a geo-environmental hazard based to high level design standards. It is pertinent to mention that resilience in general and consequently the implementation of design standards, hence cost implications, are site-specific. Therefore, the adoption of a certain resilience objective can result in different costs according to the region but also depending on the hazard as different geo-environmental hazards pose different risks hence require specific variables to be taken into account.

As formerly alluded to, the model allows a certain degree of uncertainty. However, there is negative correlation between the degree of uncertainty and the ability of the model to capture resilience effectively. To this regard, the accuracy is highly dependent on the type and quality of the model adopted. As an example, the expert-based approach proposed by Uzielli et al. [78] is numerical but involves a certain degree of subjectivity in the weight assignation when scoring the different indicators representing resilience (i.e., construction age, foundation type and structural typology). Having all this considered the natural research problem is represented by the identification of the indicators expressing resilience from a quantitative and qualitative perspective, which is going to be addressed later in this section. Additionally, it is pertinent to highlight the output of the proposed model in terms of resilience assessment should not necessarily be restricted to continuous numerical values (e.g., normalised values between 0 and 1) but it can also involve fuzzy concepts and linguistically understandable expressions (e.g., high, medium, low resilience).

When dealing with resilience, the concept of vulnerability becomes of primary importance. Without the potential of undergoing disruption, resilience would not be visible. Vulnerability, as mentioned in previous sections, therefore encompasses the likelihood and the extent of an element/system to be affected by a disrupting event. As a consequence, if a structure shows higher resilience in relation to a specific threat, this would translate into lower vulnerability even though there are additional factors to be considered. The proposed formulation for vulnerability is therefore presented in Equation 3.2 where $V_d$ stands for the vulnerability as a function of the set of variables included in the parentheses. Notably, vulnerability is here defined as a function of resilience $R_d$, and not vice versa.

$$Vulnerability = V_d(R_d, G_d, N_e, S_e, U_v)$$

**Equation 3.2:** Generic formulation of vulnerability [43].

Similarly to resilience, the concept of vulnerability is also expressed in respect to a target object (which properties are included in the resilience formulation) and a specific geo-environmental hazard $G_d$. Additional influencing factors are also resulting from the natural environmental $N_e$ and social environment $S_e$. Similarly to resilience, also the vulnerability models entails a certain degree of uncertainty which is quantified and represented by $U_v$. A natural environment is here meant to include site-specific conditions in relation to soil, weather, natural resources and topography. The social environment includes instead different features such as culture, ethnicity, beliefs, work, education and economic features. This leads to maintain that different natural, social and hazard-related features would result in different degrees of vulnerability with respect to the analysed built environment. Given also the definition of risk considered as the product of vulnerability, hazard probability and exposure and considering that the latter is factored into the formulation of vulnerability, the risk assessment can therefore be attained.

In light of the above and as a result of the extensive review presented in Chapter 2, the proposed framework will entail the consideration of two complimentary scales of analysis. In order for a built-environment resilience assessment to be comprehensive, there is the need of considering both the building-scale and the district-level given the different implications for resilience as well as the level of details required for those scale of analysis. Namely, while the micro-scale (i.e., building-level) would focus on the performance of the individual building from a purely structural perspective, the macro-scale (i.e., district-level) would account on the built-environment holistically considering it as part of a wider ecosystem. In fact, when considering urban system in its entirety, the detailed structural consideration of a building is not relevant for the underpinning consideration of resilience that at the macro-scale acquires organizational and management properties in addition to the merely technical ones featuring the building-level.

As formerly explained, the presented methodology is mainly constituted by two threads of research, namely district (i.e., macro) and building-scales (i.e., micro). The two strategies eventually interlace in the context of damage and risk prediction in face of seismic hazards at the urban level. An overview of the three scales of analysis is introduced in the ensuing three sections as the detailed outline will be provided in separate Chapters. To clarify the terminology adopted from this point forward, Figure 3.3 presents the distinction between research methodologies as described in §3.1, research threads as per the current section and the corresponding label.

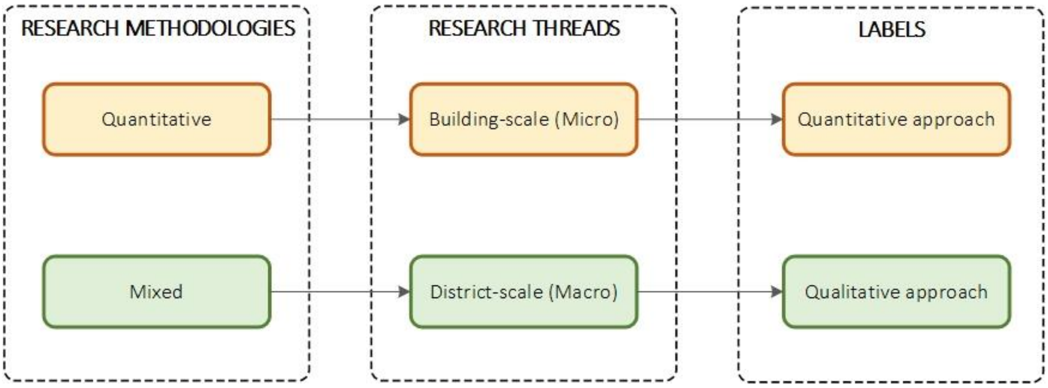


**Figure 3.3:** Distinction between research threads, methodologies and labels adopted for the proposed work.

## 3.3. Case-study: the 2008 Wenchuan Earthquake

The previous section described the proposed framework for resilience which also factors the main findings from the literature review outlined in Chapter 2. To provide a solid ground evidencing the applicability and effectiveness of the proposed methodology, a real scenario was adopted and specifically the 2008 Wenchuan Earthquake in China. This was contextualized in the frame of the REACH project, aiming at increasing the understanding of resilience from a holistic perspective in face of seismic hazards, specifically targeting the Wenchuan province in the aftermath of the earthquake occurred in 2008.

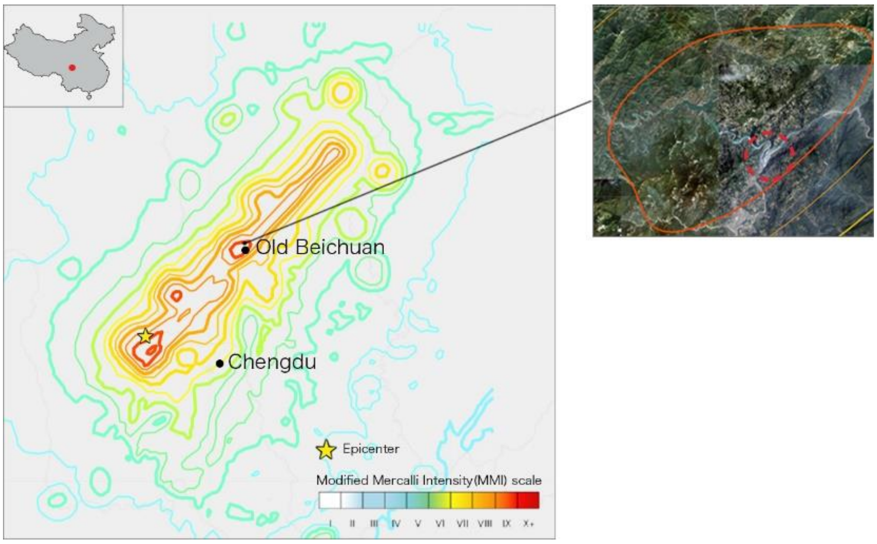


**Figure 3.4:** Modified Mercalli Intensity (MMI) distribution and geographic localisation of study area [Modified based on USGS database].

The Wenchuan earthquake occurred on the 12th of May in 2008 and a maximum recorded magnitude of 7.9 on the Richter scale was registered [237]. Research evidences that the main energy release zone was identified along the crustal Longmen and Anterior faults [238], being Old Beichuan located along the main rupture surface area [239]. Figure 3.4 contextualizes the epicentre of the earthquake in the China providing also a distribution of the seismic intensity along the Longmen fault and measured according to the Modified Mercalli Intensity (MMI) scale. Old Beichuan is highlighted in the map having been selected as the main focus for this research given the extensive building stock which is still preserved and accessible from the main roads of the town.

The REACH project encompasses a holistic perspective of resilience, factoring into the framework also the sociological aspect and therefore providing an innovative perspective on disaster resilience. As presented in Figure 3.5, the main project workflow is divided into 4 research threads (i.e., A, B, C and D), each pertaining a different progress level of the project. It is pertinent to observe that the main contribution of this research pertains the technical aspects related to the resilience of the built environment. Additionally, the proposed schematization of the project workflow is just representative of the main research tasks not attempting to be representative of the whole picture.

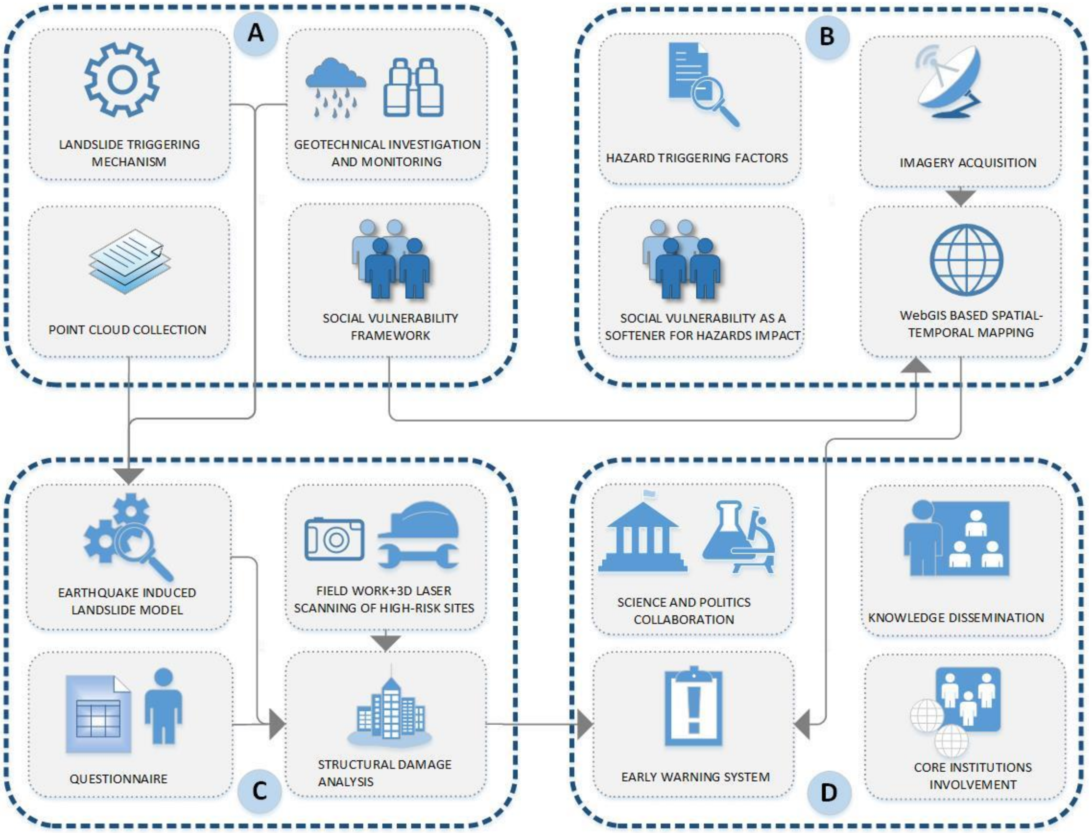


**Figure 3.5:** Schematization of REACH project workflow [44].

Research threads A and B mainly target knowledge acquisition and a preliminary elaboration of data for the formulation of initial hypotheses in relation to the hazard triggering factors. The data acquisition is carried out through the direct 3D laser scanning for point cloud collection and field investigations as well as through satellite imagery analysis. Research thread C progresses through the elaboration of the material acquired over the former stages and the resulting outputs are therefore disseminated to foster a more risk-based design for buildings and infrastructures and its factorization into regulatory frameworks. A noteworthy aspect of the last project thread pertains to the potential for early warning systems to safeguard human lives and their application for damage-prediction thanks to the opportunity of real-time monitoring and data collection.

## 3.4. District-level resilience

Chapter 4 aims at answering research question 1: *Can a disaster management framework be developed to address buildings' resilience at the district level with a holistic consideration of related factors?* The literature review demonstrated how current strategies addressing disaster resilience from a district-level perspective tend to lose accuracy and focus due to the attempt of covering an excessive amount of potential hazards and objective. Chapter 4 will therefore entail the development of a qualitative strategy to investigate the resilience of the built environment in face of seismic hazards. This is attained through the identification of a series of governing features and their assessment was carried out via Delphi expert consultation. The consultation process took place between November 2017 and February 2018, entailing a total of 48 criteria and 21 respondents between REACH project partners and experts identified through the literature review. The criteria were scored through two rounds of consultation and the results were processed adopting statistical indicators as flags for the relevance of the indicator.

As outlined in section 2.2.2, other approaches to target district-level resilience are available in the existing body of knowledge. As an example, network-based strategies have been applied across several disciplines and their strength is too account for the interdependency of the system. However, as described in section 2.2.2, such approaches would not allow to factor in non-quantifiable processes and strategies which are highly intrinsic of this scale of analysis. Resilience cannot neglect the consideration of disaster management strategies at the district scale, and consequently decision-making processes could not be factored in a highly analytical approach without leading to a significant level of uncertainty and therefore undermining the adoption of such technique.

## 3.5. Building-level resilience

The building-level resilience assessment and enhancement stage coincides with the micro-scale of the presented methodology at the beginning of the Chapter and it will be extensively encompassed in Chapter 5. As opposed to the district-level approach, this level of analysis requires the execution of analytical tasks and a more focuses understanding of the buildings' behaviour from a structural perspective. This research thread therefore aims at enhancing traditional approaches to investigation and damage forecasting in relation to structures. This is attained through the implementation of artificial intelligence techniques, such as evolutionary algorithms and neural networks with an increasing level of complexity and abstraction with the progression of the research tasks.

This approach entails the deployment of three subsequent research stages, informed by a preliminary knowledge acquisition of the building conducted through field investigation techniques (i.e., inspections, 3D laser scanning), semantic modelling of buildings and structural simulations. Research questions 2-4 are respectively addressed in each of the core stages of this approach and they can be summarised as follows:

- Stage 1: Investigation of specific building features through the deployment of a GA in combination with the Autodesk Robot API; this stage addresses research question 2: *How can structural design parameters be inferred to accurately characterise and model a seismically compromised building in case of limited access to data and lack of supporting documentation?*
- Stage 2: The Robot API is iteratively invoked to perform a significant number of simulations and sensitivity analysis is conducted to identify the governing variables for the building's performance. Ultimately, the amount of data is reduced utilizing Principal Component Analysis in order to train an ensemble of neural networks. This stage encompasses research question 3: *Can the governing variables most sensitive to the structural integrity of a building be inferred taking into account a wide range of considerations, including local environmental and geotechnical conditions?*
- Stage 3: the Robot API is replaced with a neural network ensemble and the whole engine is deployed to perform damage forecasting adopting a performance-based approach. Ultimately, stage 3 aims at answering research question 4: *Can these sensitive variables inform the development of less computationally demanding structural analysis models with a view to optimize the structural design of a building?*

It is pertinent to mention that the structural simulation conducted on the building consists in linear-dynamic analysis (i.e.,modal), given the impossibility of pursuing a pushover method due to the lack of specific information to characterize the plasticity of the frame nodes. Nonetheless, this does not represent a limitation for the research approach given the full capability of integrating any desired analysis strategy through the API of Robot.

The contribution of this research thread consist in its applicability for building features optimization (e.g., geometry of the frame, reinforcement or infill properties) as well as the potential to target the design on the expected hazard intensity and expected damage through the adoption of authoritative Engineering Demand Parameters (EDPs).

### 3.5.1. Techniques

This research approach will exploit artificial intelligence techniques to enhance traditional structural analysis. The background of the employed techniques has been extensively presented in Chapter 2, therefore the following sections aim at discussing at a preliminary level the machine learning features adopted for the scope of this research.

#### *3.5.1.1. Genetic algorithms*

Referring to the above outline of research stages, it is evident how the application of GA is twofold, namely addressing both stages 1 and 3. For the purpose of the optimization, the Optimization Toolbox available in MATLAB was employed. Both node displacement and IDR were adopted as objectives for the GA with single and multi-objective optimization strategies. Namely, both the EDPs can be represented by 3-directional components in x, y and z. The single-objective optimization adopts the aggregated displacement as an objective, represented by the sum of the values for each direction. On the contrary, when adopting a multi-objective optimization, the value for the EDP in each direction represents an objective.

Time is usually a critical factor for genetic algorithms and specifically when coupling them to a software API, such as the case of stage 1 for this research. In order to optimize the performance of the algorithm, an output function was devised such as to force the stop the iterations when the discrepancy between the attained value and the objective was less than 0.0001 cm. Additionally, after running a series of simulations, it was observed that with a population between 80 and 100 individuals the algorithm tended to converge after about 15 generations. As presented in Table 1, a population of 80 individuals and a total of 30 generations were featured for stage 1.

Conversely, stage 3 entailed the combination of the GA with neural networks resulting in a significant enhancement of the simulation time. This led to increase the population number to 200 individuals and the generations to 50 as no significant variability was observed for higher generation numbers (e.g., 100). The variability of individuals for each generation was therefore favoured over the generation numbers.

**Table 3.1**: Genetic Algorithm features for research stages 1 and 3.

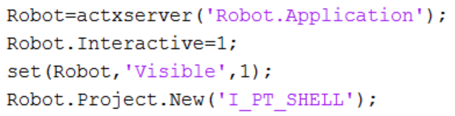
| Research stage | Variables | Generations | Population |
|---|---|---|---|
| 1 (GA + API) | 2÷7 | 30 | 80 |
| 3 (GA + ANNs) | 2÷7 | 50 | 200 |

##### *3.5.1.2. Artificial neural networks*

Grounding on the research stages previously outlined, it is possible to recall how the neural network integration mainly applies to stage 3, as their objective is to replace the structural behaviour software. Namely, this research adopts a *feedforward backpropagation* neural network trained through *Bayesian Regularization* featured by 4 hidden layers where the first 2 present 5 nodes and the last two have 2 nodes. As it will be further explored in Chapter 5 in the pertaining section, the determination of the optimum ANN size stems from a trial-and-error strategy aiming at manually optimizing the best neural network for the research task. This is attained by a calibration of the number of nodes for each layer at each variation of the number of layers to avert the risk of overfitting. Given the multilayer nature of the neural network, the transfer function adopted for the ANN training is *logsig*.

### 3.5.2. Integration between structural behaviour tool and MATLAB

As formerly introduced in relation to the approach adopted for the quantitative portion of the research, it is herein attempted to automate specific tasks and calculations as well as structural analysis by implementing MATLAB with the structural behavior simulation tool. This entails relying on the API (Application Programming Interface) to remotely perform object manipulation and iterate structural behaviour simulations benchmarking specific variables in the MATLAB environment. This is mainly attained establishing the connection amongst the two software by means of COM technology and using the command “actxserver” as in Figure 3.6. It is therefore allowed to set the Graphic User Interface (GUI) visible and interactive through the pertinent commands as presented in Figure 3.6. Throughout the procedure the GUI remains accessible for the user to interact with, and changes occurring in the model either through the GUI or MATLAB are equally acknowledged by the software.



```
Robot=actxserver('Robot.Application');
Robot.Interactive=1;
set(Robot,'Visible',1);
Robot.Project.New('I_PT_SHELL');
```

**Figure 3.6**: Connection establishment between structural simulation tool and MATLAB.

Once the connection between the tools has been established, the simulation tool appears in MATLAB in the form of an object featured by a tree structure as in Figure 3.7. Each element of the API can be invoked by means of a querying strategy that instructs MATLAB to navigate through the tree structure following a specific path. As an example, Figure 3.6 proposes the query to create a new project. It is pertinent to mention that the presented API structure is representative of just the main servers contained in it.

It is noteworthy to mention that the API is structured into servers and objects. Servers consists in complex ensembles allowing the manipulation of objects. Objects instead are the visible model components which are characterized by a series of properties and can be manipulated through the pertaining servers. Examples of servers are for instant the BarServer or the NodeServer, which respectively contain bars (i.e., linear structural and non-structural members) and nodes. As a clarification, columns and beams are classified as bars while the nodes consist in the non-dimensional elements defining the extremes of each bar or panel.

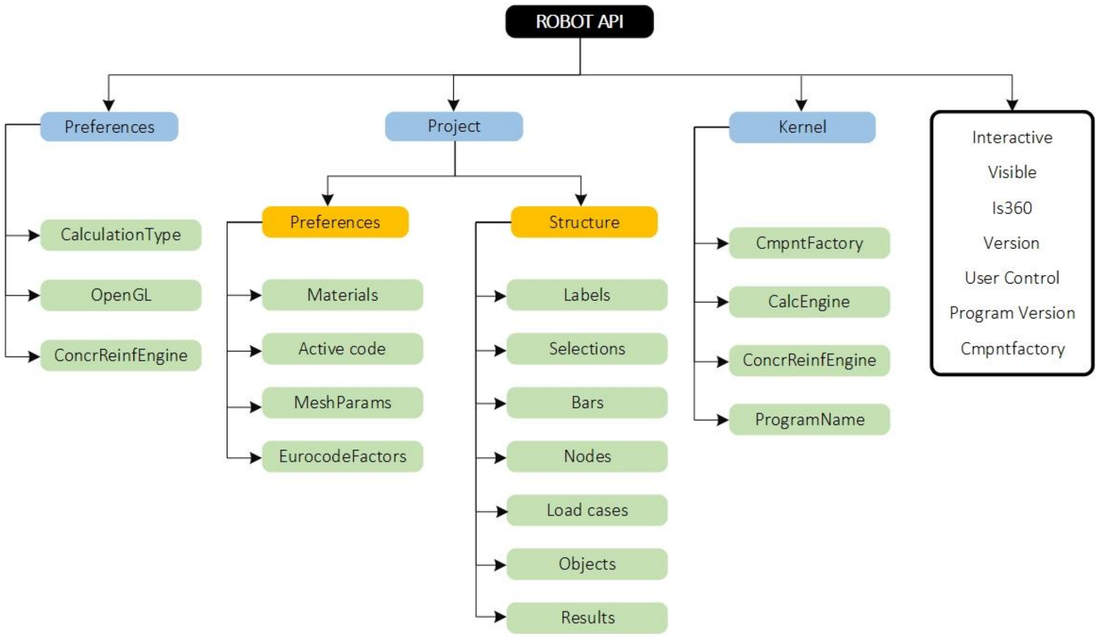
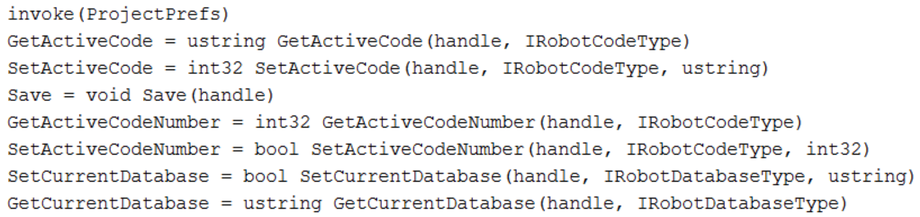


**Figure 3.7**: API structure [213].

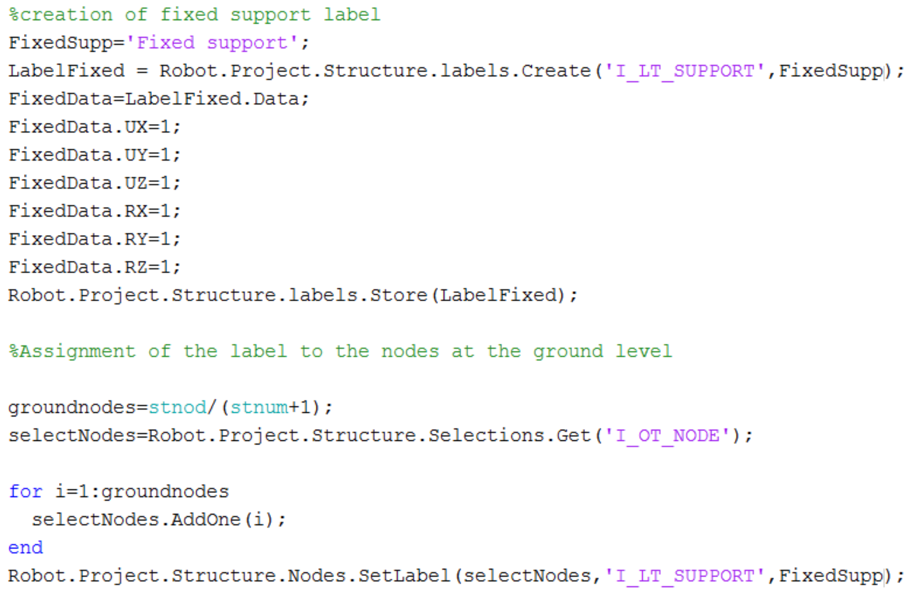
As this API is extensively documented just in relation to C#, C++ and Visual Basic environments while there is no content regarding MATLAB, it was necessary to investigate the available commands and queries through the “invoke” function as shown in Figure 3.8. This command allows gathering ofan extensive list of allowed operations for specific servers in order to then query it and operate on the objects such as in Figure 3.6. In the specific case of Figure 3.7, the Project Preferences (ProjectPrefs) are considered and it is evident how the output of the application of the “invoke” command is twofold. Each line contains in fact a command with the pertinent output and inputs. As an example, the GetActiveCode command, providing the building code adopted for the calculation and verification, provides a string (ustring) value in output, but requires a handle (i.e., object) and a string or magic number identifying the building code typology (i.e., IRobotCodeType).



```
invoke(ProjectPrefs)
GetActiveCode = ustring GetActiveCode(handle, IRobotCodeType)
SetActiveCode = int32 SetActiveCode(handle, IRobotCodeType, ustring)
Save = void Save(handle)
GetActiveCodeNumber = int32 GetActiveCodeNumber(handle, IRobotCodeType)
SetActiveCodeNumber = bool SetActiveCodeNumber(handle, IRobotCodeType, int32)
SetCurrentDatabase = bool SetCurrentDatabase(handle, IRobotDatabaseType, ustring)
GetCurrentDatabase = ustring GetCurrentDatabase(handle, IRobotDatabaseType)
```

**Figure 3.8**: Example of adoption for the invoke function.

Another relevant consideration regarding the objects addresses the creation of “labels”. In the context of this API, a label is a set of properties that distinguish an object from another although pertaining to the same family. An example can be provided with respect to the constraints, as shown in Figure 3.9.



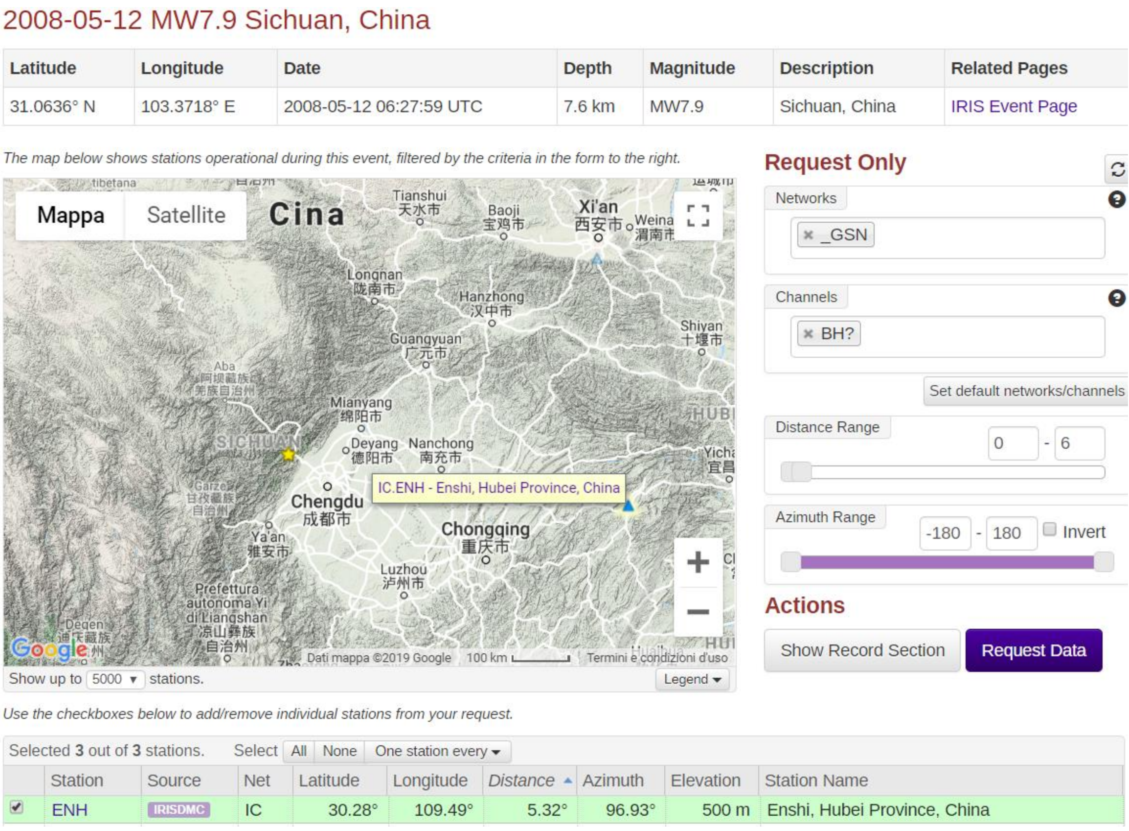
```
%creation of fixed support label
FixedSupp='Fixed support';
LabelFixed = Robot.Project.Structure.labels.Create('I_LT_SUPPORT',FixedSupp);
FixedData=LabelFixed.Data;
FixedData.UX=1;
FixedData.UY=1;
FixedData.UZ=1;
FixedData.RX=1;
FixedData.RY=1;
FixedData.RZ=1;
Robot.Project.Structure.labels.Store(LabelFixed);

%Assignment of the label to the nodes at the ground level

groundnodes=stnod/(stnum+1);
selectNodes=Robot.Project.Structure.Selections.Get('I_OT_NODE');

for i=1:groundnodes
  selectNodes.AddOne(i);
end
Robot.Project.Structure.Nodes.SetLabel(selectNodes,'I_LT_SUPPORT',FixedSupp);
```

**Figure 3.9**: Label creation for fixed constraints.

A label is created to characterize fixed constraints at the base of the structure and this is attained querying the labels server through API structure and adopting the function “Create” with the string identifying the element to be created (i.e., support label type, I_LT_SUPPORT) and the bespoke name (i.e., FixedSupp). Following to that, the label object properties are accessed through the ensuing command LabelFixed.Data and is it therefore possible to prevent translations and rotations in specific directions according to the desired constrain condition. In this case a fixed constrained was created, therefore both traslations (i.e., UX, UY, UZ) and rotations (i.e. RX, RY, RZ) were prevented. In order to finalize the creation of the label, this has to be stored as shown in Figure 3.9 and then applied directly to the designated selection of elements (i.e., selectNodes).

### 3.5.3. Generation of seismic acceleration spectra through velocity time series

Given the unavailability of direct measurements for either accelerations or displacements, the IRIS Wilber 3 online database was selected as a source of information [240]. Here, the velocity time series were downloaded in the three spatial directions corresponding with the East-West, North-South and Z (i.e., vertical) axes. The data available through Wilber represents direct measurements of velocities which has not however been processed to remove potential noise. Figure 3.10 presents the Wilber 3 interface with the details of the event and the selected station for data collection.



2008-05-12 MW7.9 Sichuan, China

| Latitude | Longitude | Date | Depth | Magnitude | Description | Related Pages |
|---|---|---|---|---|---|---|
| 31.0636° N | 103.3718° E | 2008-05-12 06:27:59 UTC | 7.6 km | MW7.9 | Sichuan, China | IRIS Event Page |

*The map below shows stations operational during this event, filtered by the criteria in the form to the right.*

Request Only

Networks: _GSN

Channels: BH?

Distance Range: 0 - 6

Azimuth Range: -180 - 180 ☐ Invert

Actions

Show up to 5000 stations.

*Use the checkboxes below to add/remove individual stations from your request.*

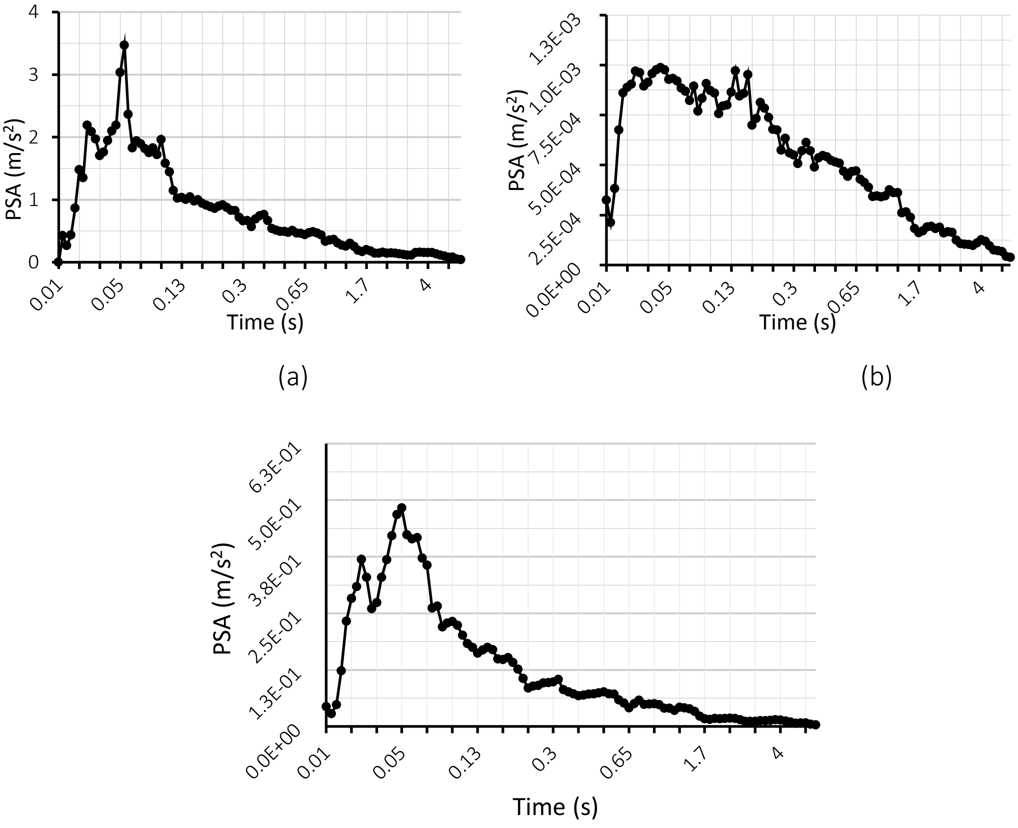
Selected 3 out of 3 stations. Select All None One station every

| | Station | Source | Net | Latitude | Longitude | Distance | Azimuth | Elevation | Station Name |
|---|---|---|---|---|---|---|---|---|---|
| ☑ | ENH | IRISDMC | IC | 30.28° | 109.49° | 5.32° | 96.93° | 500 m | Enshi, Hubei Province, China |

**Figure 3.10**: IRIS Wilber 3 interface and location of the closest station to the epicentre.

A first glance at the map reveals however that the considerable distance between the epicentre and the station location may result in attenuated values due to a series of concurrent factors and uncertainties. The distance between the epicentre leads to the consequential dampening of the seismic acceleration, which is also due to the potential change of terrain and it is conditional on the depth of the epicentre.

The velocity data were collected between 1 minute before and 10 minutes after the P-wave arrival. However, the time series data collected by the seismometer are not in Earth units (i.e., m/s), but Counts. The conversion to unit measure was performed as described by IRIS ([https://ds.iris.edu/ds/support/faq/6/what-is-a-count-in-timeseries-data/](https://ds.iris.edu/ds/support/faq/6/what-is-a-count-in-timeseries-data/)) by simply deriving each time series velocity by the specific conversion rate for the selected station. Once the velocity values were converted, acceleration and displacement data were calculated respectively through derivation and integration. Following to that, the pseudo-spectral accelerations (PSA) were derived adopting the methodology proposed by Wang [241]. This approach was adopted for all the three aforementioned directions and the final PSAs are plotted in Figure 3.11.



(a)

(b)

(c)

**Figure 3.11**: PSA spectra for North-South (a), East-West (b) and vertical (c) directions.

## 3.6. Extrapolation from building to district-level

Sections 2.2 and 2.3 highlighted that qualitative and quantitative approaches for resilience assessment are usually tackled separately. Besides, resilience assessment strategies are also rather granular given the lack of contextualization into a larger and more holistic perspective, hence resulting in an overall scattered existing body of knowledge. As a result, this research aimed at averting this phenomenon by providing two separate scales of analysis and the potential for their implementation, as it will be presented in Chapter 6.

The final stage of the research entails the combination of the two scales of analysis in order to pursue a risk-based conceptualization of resilience at the district level. This would produce a concrete and evidence-based resilience assessment of the buildings from an analytical perspective which would then feed into the urban-level framework. In the context of the adopted validation scenario and given the impossibility of characterizing all the building stock in Old Beichuan, an extrapolation was conducted in order to assess the predicted damage to other structures in the district using the Beichuan Hotel structure as a reference point. Chapter 6 will therefore extensively outline the contributions of this final stage.

## 3.7. Conclusion

An overview of the global research methodology was proposed in this Chapter whereas the detailed approach adopted for each of the research threads is addressed in pertaining Chapters. Chapter 3 also provided a theoretical motivation for the adopted research approaches, labelled for this research as quantitative (i.e., micro-scale) and qualitative (i.e., macro-scale), however adopting respectively a quantitative (i.e., numerical) and mixed research methodologies. While the district-scale research thread directly links to resilience management strategies in face of geo-environmental hazards, adopting a Delphi-based consultation, the building-scale is instead featured by three stages with increasing level of abstraction. Namely, the techniques adopted for the micro-level approach are artificial neural networks, genetic algorithms and principal component analysis.

The adoption of such methodologies (i.e., qualitative and quantitative) in relation to different scales of analysis is motivated by the nature of the objectives to be pursued at different levels. At the district level, the complex socio-technical system featuring the urban dimension prevents the adoption of a merely analytical strategy given the often non-quantifiable factors involved. At this scale of analysis a great role is played by decision-makers, hence a good proportion of uncertainty is involved due to the great human component involved. At the district scale the main objective is in fact how to attain resilience through an effective emergency management, both in terms of pre and post-disaster policies and strategies.

Conversely, at the building scale the analysis is purely numerical given that the objective is to attain resilience through the only structural performance of the building. The latter therefore relies upon a set of criteria which are linked merely by mathematical relationships and therefore the need for an analytical approach to be capable of dealing with such variables’ interplay is necessary. Therefore, the whole framework exhibits a hybrid nature, featuring both a qualitative strategy addressing the urban scale and a quantitative performance-based approach targeting the building-level.

# 4. District-Level Resilience Assessment

As evidenced by the extensive literature review in Chapter 2, there is a consistent agreement both in academia and industry in relation to the need of developing tools able to assess and enhance the resilience of the physical environment in face of geo-environmental hazards. Following to the previously outlined methodology, this section will address in detail the development of the district-level resilience framework and its originality compared to existing tools.

## 4.1. Revisiting research questions

The current Chapter aims at answering research question 1, restated here as follows:

*Can a disaster management framework be developed to address buildings' resilience at the district level with a holistic consideration of related factors?*

Addressing resilience at the district-scale with the purpose of evaluating the built environment's ability to cope with a hazard requires an approach able to factor in a wider consideration of the urban context, not just involving technical aspects. To attain this, it is required to define a set of features, or criteria, able to characterize the governing aspects and domain that determine the final resilience outcome for a specific urban system. Disaster management resilience, in fact, does not just apply to the technical aspects related to micro-level resilience, but it entails the consideration of governmental and organizational features. These, have to be factored into the framework through the adoption of a holistic approach which leads to include a series of external factors (e.g., environmental, organizational and infrastructural) that have directly or indirectly an impact on the final resilience performance in face of a geo-environmental hazard. As outlined in both Chapter 2 and 3, the Delphi expert consultation provides a valid contribution and allows to systematically improve the framework thanks to the feedback provided by a selected panel of experts. The work proposed here was initially published by Cerè et al. [100] and it has been reformatted and proposed here in an extended version.

## 4.2. Development of Delphi consultation process

The methodological approach adopted in the context of the district-level resilience assessment entails the creation of an overarching framework constituted by a series of criteria grouped into different categories. In order to identify each of those, an initial review was carried out in relation to existing frameworks and their structure. The review therefore aided a preliminary identification of the macrostructure of the proposed district-level resilience framework and a more in depth review concerning each of the categorised was carried out to identify the specific criteria. To further select and validate the governing criteria a Delphi consultation was carried out between November 2017 and August 2018. Figure 3.1 shows a schematic of the strategy employed to conduct the Delphi consultation, commencing with the aforementioned review phase which aimed at examining existing framework addressing the characterization of resilience from the perspective of the built environment.

**Figure 4.1:** Delphi consultation methodology [100].

Given the multi-faceted nature of resilience it is beneficial to rely on an expert consultation strategy such as the Delphi. The employment of this technique allows to factor the feedback of different experts in relation to specific fields and within an established timeframe. The choice of this strategy over others is supported by its adoption in a significant amount of research works. Construction engineering and management-related disciplines have been employing it extensively according to the research by Ameyaw et al. [242]. Sourani et al. [243] argue this position highlighting that the construction industry generally favours questionnaires over Delphi elicitations and one of the main criticalities of the process is maintaining the same response rate across the rounds. A pertinent example is however provided by Kermanshachi et al. [244], who employ a Delphi elicitation to assess the most effective management strategies when dealing with complex projects in the construction domain. On a different note, Alshehri et al. [94] propose a socio-organizational assessment of resilience targeting communities. Similarly to Alshehri et al., Labaka et al. [81] employed a Delphi elicitation however encompassing resilience management strategies.

### 4.2.1. Delphi expert consultation

A Delphi-based expert elicitation broadly consist in an iterative procedure aimed at validating a series of statements. The number of rounds necessary to ensure the reliability of the results usually is a minimum of two [245, 246] but a higher amount [242, 247] can be pursued. The statements intended to be validated are submitted to a panel of experts selected from relevant domains and then scored according to their individual judgment and grounding on the domain knowledge. This strategy allows to involve a geographical variability of the experts included in the panel and it is of specific use when the collection of results can be conducted over a longer period of time [248]. Grounding on existing research, the Delphi elicitation strategy is praised due to four main advantages:

- Experts' anonymity;
- After each round the experts can change their view on any of the statements;
- The provision of feedback allows to inform the experts about the outcome of the former round of elicitation;
- A statistical analysis is conducted on the final round responses and allows to comprehensively account for each expert's opinion [94, 249–251].

### 4.2.2. Panel of experts

Given the lack of an established standard regarding the panel of experts' size[247, 252, 253], existing research has been analysed as in Table 4.1, where scoring scale, initial and final respondent numbers are listed. Witkins and Altschuld [254] however recommend a maximum panel size of 50 experts whereas according to Clayton [255] it is relevant to differentiate amongst homogeneous and heterogeneous panels. All this considered and given the response rate of the research presented in Table 4.1, a panel size of minimum 50 experts is adopted in order to pursue a more inclusive approach towards different domains and geographical areas.

**Table 4.1:** characteristics of different Delphi methodologies.

| REFERENCE | SCALE TYPE | INITIAL PANEL SIZE | FINAL RESPONDENTS |
|---|---|---|---|
| Alshehri et al. [94] | 5-point Likert | 71 | 40 |
| Labaka et al. [81] | 5-point Likert | 21 | 15 |
| Elmer et al. [256] | 6-point bipolar | 55 | 45 |
| Jordan et al. [248] | 5-point scale | 12 | 11 |

The experts were selected based on a pertinent literature review addressing natural hazards and their impact on the resilience of the built environment [43]. The involvement of both industry and research-based institutions as well as academic bodies provides an interdisciplinary expertise background which benefits the final results' quality. Furthermore, experts from China and United Kingdom joined the panel as partners of a project aiming at enhancing resilience to seismic hazards and in particular targeting the 2008 Wenchuan Earthquake. As also presented in Figure 4.2, a focus group was devised in order to submit paper questionnaires to the experts from China. The Delphi consultation was conducted over two separated rounds both for the online and paper questionnaires and the overall breakdown of experts' domain of expertise is provided in Table 4.2.

**Table 4.2:** Distribution of experts by domain of expertise.

| Domain of expertise | After 1st round | After 2nd round |
|---|---|---|
| Earthquake engineering | 3 | 2 |
| Geotechnical engineering | 4 | 4 |
| Urban planning and sustainability | 1 | 1 |
| Geology and risk assessment | 11 | 11 |
| Multi-hazard and reliability analysis | 2 | 1 |
| Urban, social and environmental resilience | 1 | 1 |
| Geotechnical and earthquake engineering | 1 | 1 |
| **TOTAL** | 23 | 21 |

As it can be observed from Table 4.3, the initial panel of experts included overall 70 people from 18 countries and although a consistently low initial response rate of 23 experts was registered, 21 joined until the last round. Table 4.4 outlines instead the distribution of the experts based on professional bodies and their response rate across the two rounds of consultation. Despite the initial predominance of Academics, after the second round a more balanced distribution was attained as opposed to the previous ones.

**Table 4.3:** Geographic distribution of experts across the Delphi consultation rounds.

| Country | Initial panel of experts | % | After 1st Round | After 2nd Round |
|---|---|---|---|---|
| Italy | 17 | 24 | 2 | 1 |
| United Kingdom | 16 | 23 | 4 | 4 |
| USA | 12 | 17 | 4 | 3 |
| China | 7 | 10 | 7 | 7 |
| Norway | 3 | 4 | 1 | 1 |
| Germany | 3 | 4 | 0 | 0 |
| Colombia | 1 | 1 | 1 | 1 |
| New Zealand | 1 | 1 | 0 | 0 |
| Spain | 1 | 1 | 0 | 0 |
| Austria | 1 | 1 | 1 | 1 |
| Slovenia | 1 | 1 | 0 | 0 |
| Netherlands | 1 | 1 | 1 | 1 |
| Saudi Arabia | 1 | 1 | 1 | 1 |
| Greece | 1 | 1 | 0 | 0 |
| Turkey | 1 | 1 | 0 | 0 |
| Iran | 1 | 1 | 0 | 0 |
| Canada | 1 | 1 | 0 | 0 |
| France | 1 | 1 | 1 | 1 |
| **TOTAL** | 70 |  | 23 | 21 |

Prior to the consultation, the experts were informed and invited either personally or via email link to the online questionnaire. A description of the research purpose and further use of the collected data was provided as well as the guarantee of anonymity. The experts were also made aware about the time that they could allocate to fill the proposed survey, which would not exceed 20 minutes. The first round was carried out by means of an online survey tool, namely the former Bristol Online Survey (BOS) and current Online Survey (https://www.onlinesurveys.ac.uk/). Given the need of integrating the feedback from the previous round of elicitation, the second phase was performed with excel forms featured for each of the respondents.

**Table 4.4:** Distribution of experts by professional background.

| Domain | Initial panel | % | After 1st round | % | After 2nd round | % |
|---|---|---|---|---|---|---|
| Academia | 37 | 53 | 10 | 43 | 8 | 38 |
| Independent research institutes | 21 | 30 | 8 | 35 | 8 | 38 |
| Consultancy and Industry | 12 | 17 | 5 | 22 | 5 | 24 |

### 4.2.3. Delphi rounds

Existing research proves that an inverse trend exists between the number of consultation rounds and the response rate [247] and to this regard Dalkey et al. [257] identify as an optimum a two-round Delphi consultation. This is due to the significant drop in response rate which is generally registered after the second round of consultation and therefore two rounds are adopted for the present research. The summary provided in Table 4.1 aided the choice of a suitable score-assignment scale and given that the highest response rate is attained when utilizing a 5-point Likert scale (1=not important, 5=most important), the latter was chosen for the current research.

As it can be observed from Figure 4.1, a preliminary trial round was conducted amongst the authors' research group in order to improve the survey in light of researchers', academics (e.g., Professors, Lecturers) and PhD students' comments. Throughout the consultation process and especially during the trial rounds, the respondents were allowed and encouraged to write comments, amendments to the criteria and also proposing new ones. In order to ensure complete coherency amongst the online survey and the focus group with the Chinese experts' delegation, the same format was preserved and the respondents were not allowed to talk between each other during the questionnaire. Discussion was conversely encouraged in between the two rounds with the scope of attaining a suitable consensus level amongst the respondents and therefore progress through the following phase.

### 4.2.4. Consensus achievement criterion

Similarly to the previous sections, no established standards existing with respect to the achievement of consensus amongst the respondents. However, consensus is a necessary condition to move from one round of consultation to the following one and therefore a thorough review was conducted with the aim of identifying the most authoritative benchmark. Although several consensus assessment strategies are available in the existing body of research [258], the interquartile range (IQR) is broadly endorsed by the research community as a reliable indicator [259]. Following to the choice of the index, the problem of the identification of the numerical threshold is therefore posed. To this regard, Rayens et al. [260] state that consensus is reached when an IQR achieves a value corresponding to less than 20% of the scoring scale. Grounding on this and considering that the present research employs a 5-point Likert scale, an $IQR \leq 1$ embodies the achievement of consensus. The lower the IQR is and the stronger the consensus achieved, with the bounds 0 and 1 respectively representing the best and the worst scenarios.

As part of the indexes adopted for the statistical analysis of the data set, standard deviation is considered functional to express the overall dispersion of the responses [261]. Namely, higher values of standard deviation coincide with undesired scattered data sets, whereas values close to zero portray a compact set of responses. Goldman et al. [262] maintain that 1.5 can be considered as a threshold for standard deviation beyond which a loss of consensus is registered. Additionally, Greatorex and Dexter [261] state that the relevance of each indicator is also represented by their mean value in terms of attained score.

### 4.2.5. Stopping criterion for Delphi consultation

Currently, no universal standardized criterion available in the literature and research to establish when and why to stop a Delphi elicitation. As a result of an in depth review of different approaches adopted in several research contexts, it was decided to employ the “hierarchal stopping criteria” strategy proposed by Dajani et al. [263] which contradicts the consideration of the IQR alone as a termination criterion. Dajani et al. maintain that the consideration of the data set stability across the different rounds is more representative than the fulfilment of the IQR index in relation to the last round of consultation. English and Kernan [264] overcome this obstacle through the calculation of the Variation Coefficient, represented by the ratio between the standard deviation and the mean value for each of the criteria. The calculation of the Variation Coefficient advocates the termination of the consultation when a negligible difference amongst the indexes of two subsequent rounds is attained. Therefore, both the IQR and the Variation Coefficient must be fulfilled in order to stop the Delphi consultation process [263]. English and Kernan [264] therefore prove that values of the variation coefficient included between 0 and 0.5 allow to confirm the achievement of consensus and then allowing the termination of the process.

Initially, the statistical analysis as described above was carried out by mean of three software in order to compare the results and specifically Statistical Package for Social Sciences (SPSS), MATLAB and Excel. However, given the bigger picture of this analysis and for coherency with respect to the quantitative part of the research, MATLAB was selected as the tool for analysis.

## 4.3. Framework for structural design

This section outlines the development of the proposed framework and the motives behind its structure. In accordance to other reviewed frameworks [5, 6, 92, 94, 95] the proposed schematization for resilience involves a multi-disciplinary structure which features a series of governing criteria grouped into categories according to their topic. A pertinent review informed the definition of the categories as well as the identification of the criteria and both were enhanced based on the author’s experience.

The proposed approach features seven categories and their definition was guided by the review of existing resilience frameworks. Namely, some of them [5, 92, 94, 95] holistically address resilience from a community perspective in face of either generic stressors [5, 95] or geo-environmental hazards in detail [92, 94]. Community resilience frameworks differ from domain-specific resilience assessments (e.g., seismic, social, network resilience) given the involvement of the social component in addition to the physical one. Burton identifies a set of persistent categories which appear to recur in several resilience studies, even though being featured by a different set of criteria. As an example, the “health & wellbeing” category which features two of the frameworks [94, 95] is not present is the 12 Cities resilience framework devised by Field et al. [5] although corresponding criteria appear to be included in “society &community”.

Table 4.5 shows the comparison across the different categories featuring the above-mentioned approaches and the proposed one, highlighting how in some instances there is a correspondence and in other cases new elements are introduced. Namely, some of the categories pertaining other frameworks have not been considered pertinent to the scope of the research and therefore they have not been included in the research approach. To this regard, it is pertinent to strengthen that the focus of this research embraces resilience in face of geo-environmental hazards specifically targeting the built environment at the district-level. The categories which feature every framework are four: governance, economy, infrastructure and environment. With respect to the economic domain, while Alsheri [94] and Da Silva [95] explicitly define it, Field [5] incorporates is to the “Business & Trade”.

**Table 4.5:** Categories in existing resilience frameworks and correlation with the proposed one.

| **Proposed framework** | **Alsheri et al.** [94] | **Field et al.** [5] | **Da Silva** [6] | **Renschler et al.** [92] | **Burton** [265] | **Cutter et al.** [62] |
|---|---|---|---|---|---|---|
| **SCALE OF ANALYSIS** | | | | | | |
| Urban | Community | Community/ urban | Community/ urban | Community/ urban | Community | Community |
| **CATEGORIES** | | | | | | |
| Environment | | | | Environment and ecosystem | Natural/ecological | Ecological |
| Governance & Planning | Governance | Governance & Economy | Leadership & Strategy | Organized government services | Institutional | Institutional |
| Utility Services | | | | | | |
| Infrastructures | Physical & Environmental | Environment & Infrastructure | Infrastructure & Ecosystems | Physical infrastructures | Infrastructural | Infrastructure |
| Emergency & Rescue systems | | | | | | |
| Economy | Economic | | Economy & Society | Economic development | Economic | Economic |
| Land use & urban morphology | | | | | | |
| | | | | Lifestyle and community competence | Community | |
| | Information & Communication | | | Social-cultural capital | | Community competence |
| | Health & Wellbeing | | Health & Wellbeing | | | |
| | Social | Society & Community | | Population and demographics | Social | Social |

One of the distinguishing aspects of the proposed frameworks pertinent to mention is the consideration of urban morphology and its effect on geo-environmental hazard impact, mitigation and recovery measures. An emerging call for compact urban structures has been raised by Godschalk [266] even though this view is contradicted by those who endorse the advantages of disperse systems in face of specific hazards. The “Land use & urban morphology” category is therefore featured by meaningful criteria such as: urban density, sprawl, elevation and distribution of urbanized lands. The vulnerability of inhabited areas has been proven to be hindered by poor urban planning strategies and to this regard Burby et al. [267] maintain that containment policies may sometimes reveals their inefficiency in preventing hazard propagation.

Sharifi and Yamagata [268] devise a review on the resilience of energy supply networks stressing the primary role of urban morphology in relation to energy distribution and access to energy sources in case of disruption. The underpinning importance of urban morphology is also evidenced by approaches integrating it with resilience and urban ecology such as the work by Marcus and Colding [269]. This leads to a comprehensive consideration of resilience which therefore raises the discipline to a more organic consideration. Dhar and Khirfan [270] propose a framework to face climate change consequences through a more sustainable and resilient urban context planning which grounds on the panarchy theory originally devised by Gunderson and Holling [271].

Utility services represent a category given their impact on the resilience of the urban system's resilience also including distribution networks for energy provision and water supplies. Few of the criteria listed within this category are in some cases shared by other frameworks [5, 94, 95], even though grouped differently. Some of the meaningful criteria pertaining "utility services" can be identified in the diversification of energy supply sources, availability of back up energy sources as well water and energy autonomy. Lessons learnt from previous hazards highlighted the need for a redundant and effective infrastructural system and a whole body of research supports this view [81, 84, 272]. As the name itself evidences, infrastructures enable the establishment of connections across urban centres allowing emergency rescue services to promptly operate and access the areas affected by a hazard. The 2008 Wenchuan Earthquake in China highlighted significant faults in relation to the lack of redundancy of the infrastructural network of Old Beichuan County, at the cost of thousands of human lives. The initial seismic event triggered a rock fall which isolated the urban centre preventing emergency rescue services to access the city hence hindering the rescue of the inhabitants. Constant health-monitoring systems for critical infrastructures have to be put in place to avert these occurrences and are accounted in the current category.

The remaining four categories are shared by all the frameworks and they will be further explored in the ensuing sections. A brief contextualization prior to the extensive description can be provided. Namely, the category labelled as "Environment" broadly aims at evaluating the system's vulnerability and it includes hazard-specific features (e.g., hazard return period and magnitude) and a set of criteria functional to characterize the context (e.g., soil properties). It is pertinent to highlight that, in order to prevent duplication when a hazard assessment of the area has already been carried out, some of the variables of this category can be omitted. Mitigation, prevention and recovery strategies for hazard emergency management are instead included in “Governance & Planning”. A primary role is also played by the local economy capacity of upholding recovery costs and the potential for NGOs to contribute through international aids.

### 4.3.1. Environment

A thorough environmental awareness in terms of surrounding characterization and hazard features is functional for the development of forward-looking strategies to mitigate the impact of a disaster and aid recovery. This is attained through a deep understanding and assessment of the exposure and vulnerability of the area, involving an accurate characterization of the natural environment as well as potential hazards in order to foster preparedness.

The potential occurrence of simultaneous disruptions is selected as a criterion for this category given the exacerbated consequences of the occurrence of multi-hazard scenarios which undermine the system’s vulnerability in different aspects. Consequently, also the geographic scale of the hazard has to be factored in due to its impact on prevention, mitigation and recovery planning.

The characterization of a hazard entails the definition of three key elements, namely the event magnitude, its spatial impact and temporal measurements [273]. As this research has a strong focus on seismic events, a clear distinction has to be highlighted with respect to hazard and risk. While the first is characterized through the event-specific features as “the probabilistic measure of ground shaking associated with the recurrence of earthquakes” [274], the definition of risk factors in the potential damage to human lives in the occurrence of the hazard. Risk is broadly defined as the combination of hazard, exposure and vulnerability [275]. In the context of the proposed research and given the focus on seismic events, the hazard investigation is carried out in light of the final framework target object, consisting in the physical built environment (i.e., buildings and structures). With respect to earthquakes it is then pertinent to express the likelihood of occurrence of a certain seismic scenario [276] as a probabilistic distribution depending on the even magnitude and that generally translates into return period. However, other geo-environmental hazards such as rock falls or landslides do not allow a straightforward forecasting, whereas the occurrence of tsunamis can be linked to seismic events and crustal-deformation can inform hazard forecasting [277]. It is worth mentioning that even though earthquakes occurrence can be estimated to a certain extent, as mentioned above, techniques usually rely on probabilistic approaches based on historical data.

With regard to the criteria involved in the environmental category, a key role is played by the characterization of vulnerability, exposure and local amplification factors. The concept of vulnerability generally accounts for the likelihood of undergoing a certain damage extent when a system is experiencing the effects of a disruptive condition featured by a given magnitude. When the hazard is represented by a seismic event the vulnerability targets the physical environment, including buildings and infrastructures. This leads to point out the relevance of ensuring high maintenance level standards in order to preserve the functionality during and after the hazardous event. It is known in fact that a poor maintenance condition increases the system vulnerability, reducing its robustness in face of hazards and hence hindering its recovery. This links to the importance of considering in-place policies and regulatory frameworks in terms of maintenance strategies. The system vulnerability is also undermined by local amplification factors, including high acidity rates in rainfall water but also pollution levels [278], being highly damaging for buildings and infrastructures.

The research work devised by Giardini [274] considers date and time of the seismic event as relevant for the vulnerability assessment in the context of risk evaluation. These factors affect in fact the level of occupancy of a building, increasing or reducing accordingly the vulnerability of human lives. However, given the scale of the proposed approach it is hardly possible to factor in these indicators also given the uncertainty involved in their determination in case of events not yet occurred. It is also pertinent to highlight the absence of the magnitude as a criterion in this category, which is motivated by its implicit consideration in the context of the return period.

Hazard intensity represents a fundamental feature to be assessed in order to characterize the resilience of a given site. A classification of different intensity measure has been carried out based on the most authoritative scales in relation to different hazard typologies, such as earthquakes, tornadoes, floods and tsunamis. However it worth mentioning that the concept of intensity differs from the one of magnitude. In this context, the intensity of the hazard applies to the qualitative vulnerability assessment. As an example, the modified Mercalli seismic scale measure the intensity, whereas the Richter one adopts the magnitude.

The overall resilience is also governed by site-specific features that determine the final integrity of the given built environment and amongst those it is possible to list soil-related properties, general weather conditions and exposure to snow. It is relevant to investigate the potential existence of ground mapping representing the basis for the foundation design of buildings and in order to prepare in face of seismically-triggered effects on buildings. As alluded to in the previous section, where a hazard assessment has already been carried out and kept up-to-date, and the indicators from 1.1 to 1.12 can be omitted in the final calculation in order to avoid duplications.

### 4.3.2. Governance and planning

This category clusters the criteria representative for the implementation of preventive and mitigation strategies adopted by governmental institutions adopted to mitigate the effects of the hazard. This specifically refers to the criterion identifying the “scale of hazard governance strategies”, representing the geographic extent of disaster prevention and recovery strategies intended for hazard management. Namely, this applies to potential relocation of people following to a disaster, allocation for resources in order to foster recovery and reconstruction but also including immediate post-disaster assessments. The need to investigate the scale of disaster management plans adopted by local governments is also endorsed by existing literature regarding resilience policies and strategies [6, 268].

The current framework factors in the need to assess the compliance to existing regulatory landscape, which accounts for the potential of unauthorized constructions often located in high-hazard areas with an increased vulnerability. It is therefore of primary importance for local governments to have a deep awareness of that in order to target disaster management policies accordingly. This also related to the consideration of the specific vulnerability of given areas which is usually considered in existing regulatory landscape and it has to be therefore factored into the resilience assessment.

Sharifi and Yamagata [268] endorse the need for data sensing techniques, which is also integrated in the proposed framework because of the potential for informing local governments and aiding the development of hazard assessments. The potential for data sensing techniques is highly disclosed for instance when having to assess and monitor the stability of slopes in face of landslide events. This strategy has been implemented in China for the development of early warning systems.

Ultimately, hazard awareness has to be developed through education in order to help young generations to attain a thorough understanding and sensitivity in relation to geo-environmental disasters. Understanding the concepts of vulnerability and hazard would enable a more efficient response which would also be fostered by regular training activities.

### 4.3.3. Utility services

The category pertaining utility services particularly applies to energy and water provision both in standard and emergency conditions. This entails the management of the pertaining networks in order to ensure an efficient service provision. Namely, it also calls for the urban capacity to provide energy and water coverage in case of disruption or in the occurrence of an infrastructural failure or isolation of the urban district. To this regard, water and energy autonomy need some essential requirements [268]. Different approaches are adopted in existing resilience frameworks, such as stressing the need for “adequate continuity for critical assets and services” [6] proposed by Da Silva, while Field [5] embeds the utility services category as a subset of the “resources” cluster. The set of indicators proposed in the present section have to be considered in the context of both new and existing constructions. Some of the criteria are for instance related to water discharge strategies, telecommunications and energy systems in place and they all demand for an accurate and forward-looking strategic planning which also entails an extensive assessment of the built-environment.

Given the need for resilience to comprehend the whole lifecycle of a system, including before, during and after conditions, an urban centre has to be provided with suitable systems to ensure energy continuity in order to facilitate emergency rescue services interventions. This links to the concept of system redundancy and diversification of energy sources or strategies for generation [268] and these principles have to guide the strategization of energy, telecommunication and water network planning. Sharifi [279] highlighted the key role of redundancy in the context of energy stocks but also regarding infrastructures. The differentiation of energy sources and production can instead be attained through the adoption of different fuels and generation strategies.

Roege et al. [280] devise a matrix of indicators for the evaluation of resilience applied to energy systems. The authors also give prominence to the concept of redundancy providing a pertinent metric for its assessment which is of particular interest in the occurrence of a hazardous event that might hinder energy provision. The metric devised by Roege et al. a 7-point scale able to qualitatively evaluate the functional redundancy of a system defined as “the ability of functionally similar elements to partly or fully substitute for each other” [280].

The reason behind the inclusion of telecommunication systems lies in their key role played in terms of emergency communications during a disaster and therefore their redundancy is of prominent importance [281]. Telecommunication systems are therefore inclusive of internet, mobile and cable lines and one of the main indicators of this category consists in the level of integration that features systems independent from potential hazard-related damages. To this regard satellite systems would logically represent the most reliable technology, however their integration in existing hazard-prone urban districts is very rare. It is more likely therefore that local governments might intent to invest in the enhancing the redundancy of network systems as it could result in a higher cost effectiveness.

Local techniques to ensure the continuity of the electric system and to avert chain failure can be identified in the adoption of circuit breakers or analogous elements [268]. Other strategies would entail the adoption of local storage energy units, or local energy power generators as well as uninterruptible power systems. On the other side, local strategies might be insufficient to cope with the high energy demand that features critical infrastructures such as hospitals.

Energy provision continuity is also fundamental for the data collection performed by structural health monitoring systems in place. If sensors are in place to register the displacements of buildings and infrastructures, this is of crucial importance during and after the seismic event in order respectively to evacuate and potentially relocate the inhabitants. In light of the above, structural health monitoring systems have to be therefore provided with a resilient system able to ensure the continuous functioning of the sensors and of the data harvesting systems necessary to elaborate those data.

Water, especially potable water, is an essential requirement to build and ensure the resilience of an urban district in face of hazardous events. During disaster management planning, suitable strategies to ensure used water treatment should be considered to enable the provision of potable water [268, 282] in case of impossibility to access a reservoir, for instance. Namely, water autonomy has to be planned in advance in order to ensure preparedness and a prompt reaction in the occurrence of the hazard.

### 4.3.4. Infrastructures

The infrastructural system can be identified with the combination of physical and organizational assets functional for the interconnectivity between elements within and outside a specific system (e.g., urban district). Within the infrastructural asset structures it is possible to include for instance roads, bridges, tunnels and other types of transportation networks (e.g., railways). Additionally, existing regulatory frameworks [33] further distinguish generic infrastructures (and structures) from the “strategic” ones, given their primary role in case of emergency. Infrastructures such as bridges or dykes can be included in this categorization. In order to ensure the functionality of critical infrastructures bespoke real-time systems have to put in place, such as health monitoring strategies. These systems are generally functional to monitor the performance of the infrastructure throughout its service life and target maintenance strategies accordingly. Another benefit of real-time monitoring techniques consists in the prevention of secondary disasters triggered by a main hazardous event. It might be the case of a strong earthquake which hinders the structural stability of a dyke or a water reservoir consequently leading to flooring and jeopardizing an entire urban centre. As alluded to in the previous paragraph, there is a consistent correlation amongst the resilience of an infrastructure and its maintenance level and strategy. Maintenance strategies are key to ensure robustness and guarantee a stable performance level even in emergency conditions [5, 64, 95].

Similar to utility services, also infrastructures' performance can be stabilized during a disaster through the provision of system redundancy. The latter is in fact identified by additional components compared to the strictly necessary amount that would suffice for its functioning. This results in an over-dimensioned system but in case of networks it results in the ability of maintaining a minimum functionality level in case of disruption. Linked to redundancy, also the level of connectivity plays a prominent role and has to be accurately calibrated in order to avert chain failures [97].

### 4.3.5. Emergency & rescue systems

The recovery process represents the final stage of the resilience process as it aims at restoring a suitable performance level in the system. Generally, the provision of efficient emergency services foster a more effective recovery process. The emergency network entails a good redundancy level of both services and infrastructures [279] but it also ensure coverage for the territory in order to prevent unattended areas. This category includes indicators which are significantly representative of the urban structure and the underpinning planning strategies but it also addresses performance upgrades of existing buildings to allow compliance with the safety regulatory framework.

As the provision and territorial coverage of the emergency network is also determined by the location of critical infrastructures such as hospitals, their distribution has to be constantly standardized in terms of mapping to the most up-to-date situation. Furthermore, shelters and safe spots must be clearly mapped as well as evacuation exits. The coherency between as-built location and existing maps has to be constantly verified and layouts need to be kept in accessible spots for the users to get familiar with those information. Specific prominence has to be given to buildings such as schools and hospitals, which need steady assessments especially in relation to potential increase in users' density with respect to design conditions, in order not to hinder the evacuation strategies.

### 4.3.6. Economy

The resilience of the physical system is undoubtedly influenced by financial availability. As a matter of fact, both the quality of the structure and technologic solutions in place have a direct impact on the final performance of a building during and after the occurrence of a hazard. As evidenced in the review chapter, poor material and structural solutions are amongst the mostly observed causes for a lack of performance.

As Briguglio et al. [283] pointed out, the Gross Domestic Product (GDP) is often a representative flag of the expected or achieved resilience of a country. It is often the case that countries exhibiting a higher financial capacity are consequently able to invest more in resilience enhancement strategies in face of hazards. Besides, being resilience a multi-faceted concept, its achievement entails research and integrated policies in a series of domains, which logically demand for financial contributions. Financial availability therefore translates into more resilient environments [283], even when international aids are available. This is endorsed by Greene et al. [284] who demonstrated the direct impact amongst construction quality standards and the GDP for a specific country. Consequently, deprived economies exhibit a lower resilience level in face of hazards. It is in fact renowned that the least wealthy urban districts are generally characterised by poor construction quality, which is of prominent relevance in contexts such as megacities (e.g., Mexico City), but also villages in underdeveloped or developing countries.

Resilience of existing structures and infrastructures can also be enhanced by adjusting them in accordance with the most up-to-date regulatory framework. The availability of financial support to endorse these initiatives would encourage more users to pursue performance-enhancement interventions, paving the way for a shorter and more efficient recovery in case of hazard occurrence. Similarly, a prompt post-disaster damage assessment of affected structures and infrastructures can inform more efficiently recovery strategies, averting potential further deterioration. Financial capacity is also a key influencing factor for the support to population affected by a disaster and needing relocation. A more efficient recovery would reduce drastically relocation periods and consequently discomfort and costs induced by the need for a temporary accommodation.

### 4.3.7. Land use & urban morphology

Research evidences that an efficient planning of land use significantly contributes to resilience when dealing with urban development [6]. Population density is also factored in as a relevant indicator [5]  and given its impact on urban planning and resilience management. Nonetheless, the consideration of population density alone without a geographic scale of analysis and a geometric characterization of the urban texture would lead to misunderstanding. In fact, similarly densely populated cities can exhibit totally different territorial extent, disaster preparedness and infrastructural robustness, consequently resulting in diverse impacts on the built environment in the occurrence of a hazard. In light of the above, this category factors in several quantifiable criteria in order to characterize the urban fabric in terms of elevation, zoning and development patterns.

The literature acknowledges urban density to be a representative indicator for the understanding of the population distribution across the urban centre [284] by taking into account the relationship between different building typologies and the variation in population. The consideration of population density alone would in fact not reflect the real urban morphology and the consequent often uneven distribution on the inhabitants on the territory. Population density is generally measured in terms of mean value, providing a “flat” representation and eliminating value fluctuations. This view is also endorsed by Loo and Ong [285], who observe that consistent variability can often be spotted in terms of population density across urban districts with similar territorial extent. The authors to this regard propose a differentiation in terms of highly dense residential areas, suburban or business areas and target the index accordingly.

The time component plays a prominent role in the understanding of how population and building densities have been evolving, namely because on a general basis density is usually represented by an average value over time and land surface, even though it is unlikely to be the case. In order to overcome this obstacle, Marinosci et al. [286] propose an approach which considers 73 cities across the Italian territory. The authors analyse the urban compactness through the adoption of GIS techniques the calculation of relevant indicators (i.e., Largest Class Path Index, LCPI) in order to evaluate the tendency of urban boundaries to expansion and the diffusion of peripheral areas. The urban dispersion phenomenon has been represented by means of two indicators, namely consisting in the dispersion index ratio and the ratio between low-density areas and the municipality boundaries. Grounding on this analysis Marinosci et al. propose a classification of different urbans structures in four different typologies, namely: (i) Monocentric, (ii) Monocentric with a tendency to dispersion, (iii) Diffuse urban structure and (iv) Polycentric. Other research [268, 284, 287] tend to classify urban patterns rather than correlating the time component to the urban development, namely proposing the following typologies: rural-urban, boundary, sprawl and compact. Marinosci et al. [286] attempt instead to identify a potential urban structure based on the sprawl index.

Given the complexity of the concept of urban structure, the introduction of the building density could aid its understating. However, the characterization of building density has to consider a series of indicators, as herein described. It is worth mentioning to this regard two indexes that the proposed framework will involve, namely consisting in the Floor Area Ratio (FAR) and the Building Coverage Ratio (BCR). While the FAR is attained through the summation of the buildings' floor surfaces over the analysed land area, the BCR in instead represented by the ratio between the buildings' footprints and the site surface [288]. For the purpose of this research, it is pertinent to observe that the FAR provides a more representative contribution of the volumetric characterization of the building stock, whereas the BCR accounts just for the external perimeter neglecting the elevation. The latter would disclose its utility when an analysis of the overall coverage of the territory would be needed, while in this specific context it is vital to give prominence to the elevation and geometry of the urban stock. To clarify the better suitability of the FAR over the BCR, it is worth observing that two land areas presenting equivalent BCR could potentially exhibit totally different FAR indexes as the vertical impact of the building stock would have an impact on the latter. In order to enable and facilitate the calculation of these indexes and the necessary buildings' height profile, Digital Surface Models (DSM) techniques could be employed.

## 4.4. Results

The Delphi expert consultation covered the time period between November 2017 and August 2018, with an initial panel of 70 experts and 40 criteria to be scored. The whole consultation combined two rounds performed through an online survey, a focus group meeting with project partners and a preliminary trial round engaging academic experts in the authors' institution. As a result of the process, the framework structure presents seven categories and a total of 48 criteria. The categories are presented in Table 4.6 as well as the amount of criteria included in each of them. In addition, a breakdown of the achieved agreement rate is provided in relation to each round of consultation. The following subsections will illustrate in detail the elaboration process undergone by the indicators in light of the experts' feedback and the pertinent statistical analysis.

A noteworthy consideration in relation to the chosen tool for statistical analysis has to be highlighted. Namely, the outputs of the first round of elicitation were initially processed through three different tools (i.e., MATLAB, SPSS and Excel), however MATLAB was adopted for consistency with the quantitative part of the framework as presented in the following chapter. A discrepancy of ±0.25 in relation to the IQR was registered for some of the proposed criteria. The combination between the different underpinning algorithms adopted by the three tools and the relatively small dataset perhaps can be considered as the motivation for the above mentioned discrepancy [289]. Following to the second round, a total of just 5 indicators were deemed as not satisfactory. Table 4.6 shows how the economic domain registered the highest surge across the two rounds, although resulting as the least satisfactory after the first one.

**Table 4.6:** Summary of results.

| Dimension | Round 1 | | | Round 2 | | |
|---|---|---|---|---|---|---|
| | Total criteria | Successful criteria | % | Total criteria | Successful criteria | % |
| Environment | 12 | 8 | 67 | 13 | 11 | 85 |
| Governance & Planning | 4 | 2 | 50 | 4 | 4 | 100 |
| Utility Services | 8 | 8 | 100 | 10 | 9 | 90 |
| Infrastructures | 3 | 3 | 100 | 4 | 3 | 75 |
| Emergency & Planning | 4 | 4 | 100 | 4 | 4 | 100 |
| Economy | 4 | 1 | 25 | 7 | 6 | 86 |
| Land use & urban morphology | 5 | 4 | 80 | 6 | 6 | 100 |
| Overall | 40 | 30 | 75 | 48 | 43 | 90 |

The online tool adopted to conduct the first round of elicitation was “Online Survey” (formerly BOS) whereas the second stage a bespoke excel form was employed. The choice of the excel form was motivated by the need of providing the experts with their responses in the former round, which was not possible in the Online Survey tool hence preventing the provision of the feedback. The excel sheets were customised in order to account for the experts’ feedback in the former round of elicitation and hence each form differed from the others in terms of content, but not in structure. Namely, each of them contained the following: (i) mean value for the responses in relation to all the criteria, (ii) standard deviation for the whole dataset, (iii) scores for each criteria provided during the previous round and (iv) the IQR for every criteria. Sufficient space for the experts to provide useful comments or suggest modifications to the criteria was also provided.

A 3-category classification was devised for the criteria in order to inform the experts about mandatory criteria to be assessed, as follows:

- Blue: The criterion achieved a satisfactory consensus level and if the respondent did not change his/her opinion, no additional scoring is needed;
- Orange: In light of experts’ feedback from the former round, the criterion was improved hence a new scoring is required even though an acceptable consensus level has been achieved;
- Red: A new scoring is required due to either the implementation of the criterion in the second round or the dissatisfactory consensus level attained.

### 4.4.1. Environment

An evident improvement in the consensus rate is registered in the second round as well as an overall higher score for the different criteria, as shown in Figure 4.2. An initial dispersion in the responses is evidenced by both Figure 4.2(a) and Table 4.7 with consistent fluctuations in terms of scoring and an evident disagreement in relation to a series of indicators, which were also regarded as not relevant (e.g., soil typology and presence of nearby hazardous industrial areas). However, it is evident from Figure 4.2(a) that a consistent improvement in both scoring assignation and agreement is acknowledged after the second round, evidenced by the decreasing height of the rectangles.

It is also pertinent to mention that in accordance to what previously alluded to, some of the indicators undergone changes in order to factor in the experts' opinion. It is the case of the first indicator, which was deemed as confusing in its initial phrasing, therefore it has been formulated in a more linear form. To this regard, the co-occurrence of potentially more than one hazard was regarded as relevant.

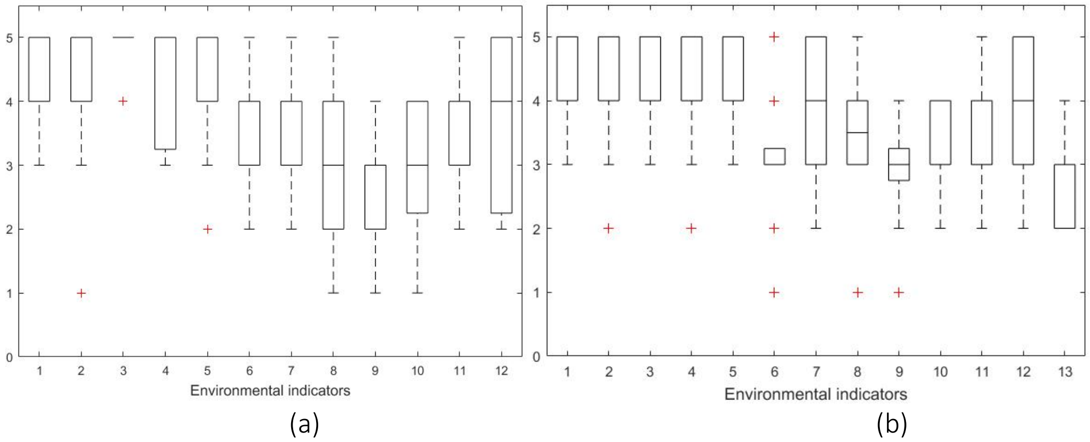


**Figure 4.2:** Environmental boxplots after the first (a) and second (b) rounds of consultation.

The experts deemed the indicators from 2 to 10 as particularly relevant, especially in the absence of a pre-existing hazard assessment for the analysed area, as also pointed out in the previous section of this chapter by the author. The fourth indicator, which was formulated as "scenario probability" was judged as inaccurate in its initial phrasing and therefore in the second round it was re-proposed in terms of hazard return period. Indicators 6 and 7 scored rather low importance over the first round having not been deemed relevant for resilience.

This is particularly evident for the "geotechnical awareness of the area" (i.e., criterion 7) which registered a significantly lower consensus rate after the second round. Amongst some of the experts' there was the view of geotechnical awareness as being more influencing over the design phase rather than for resilience itself. Two observations can be formulated in this regard, the first one consisting in the fact that the consideration of resilience entails the whole buildings' lifecycles. In addition, geotechnical awareness represents an indispensable requirement for the development of suitable mitigation and prevention strategies, but also for the reduction of hazard-prone vulnerability areas.

**Table 4.7:** Statistical analysis of results for the environment category.

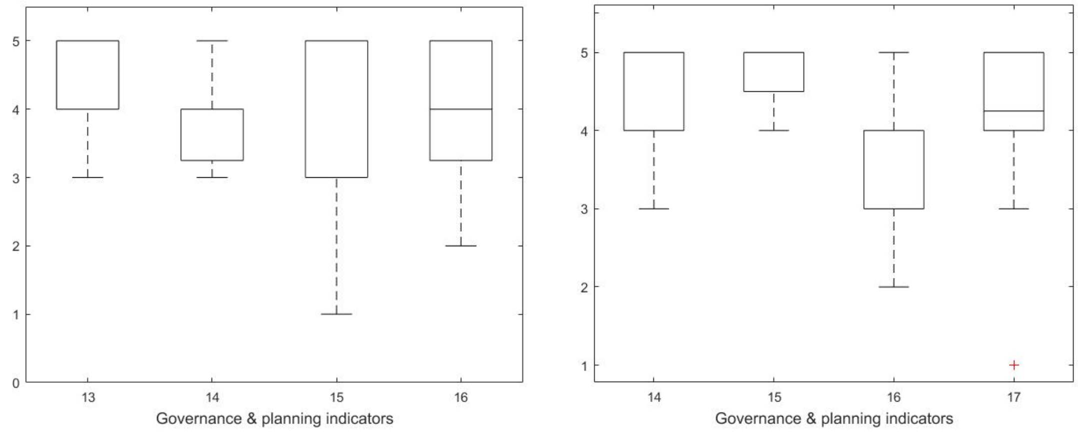
| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 1 | Single hazard (e.g., flood, earthquake, landslide, tsunami) vs multiple hazard occurrence (e.g., flood-earthquake, landslides- earthquake, earthquake- tsunami) | 4.18 | 0.795 | 1 |
| 2 | Geographical scale of hazard(s) (e.g., local, regional, territorial) | 4.18 | 0.958 | 1 |
| 3 | Intensity of hazard(s) | 4.82 | 0.395 | 0 |
| 4 | Scenario probability (i.e., likelihood of occurrence of a specific disruptive condition)/identification of the most probable scenario | 4.23 | 0.869 | 1.75 |
| 5 | Site location (e.g., altitude, urban or country area, flat or mountainous site) | 4.32 | 0.780 | 1 |
| 6 | Local environmental factors (e.g., pollution, chemical aggressiveness, vibrations) | 3.23 | 0.685 | 1 |
| 7 | Geotechnical awareness of the area (e.g., drill cores, investigations, maps) | 3.36 | 0.902 | 1 |
| 8 | Ground typology (e.g., classification according Eurocodes) | 2.91 | 0.971 | 2 |
| 9 | Level of exposure to snow (according to Eurocodes ) | 2.50 | 0.859 | 1 |
| 10 | Class of exposure to wind and terrain category (according to Eurocodes) | 3.00 | 0.976 | 1.75 |
| 11 | Level of engineering alterations with potential impact on the soil properties (e.g., mines, deforestation, fuel extraction) | 3.36 | 0.902 | 1 |
| 12 | Presence of hazardous industrial areas (e.g., nuclear plants) | 3.77 | 1.307 | 2.75 |
| | **Second Round** | **Mean** | **St.Dev.** | **IQR*** |
| 1 | Number and specific typology of hazard(s) simultaneously occurring in the disaster scenario | 4.33 | 0.730 | 1 |
| 2 | Geographical scale of hazard(s) (e.g., local, regional, territorial) | 4.24 | 0.831 | 1 |
| 3 | Intensity/magnitude of hazard(s) | 4.52 | 0.680 | 1 |
| 4 | Hazard return period | 4.10 | 0.831 | 1 |
| 5 | Site location (e.g., altitude, urban or country area, flat or mountainous site) | 4.29 | 0.644 | 1 |
| 6 | Local amplification and environmental factors (e.g., pollution, chemical aggressiveness, vibrations) | 3.10 | 0.831 | 0.25 |
| 7 | Geotechnical awareness of the area (e.g., drill cores, investigations, maps) | 3.86 | 1.153 | 2 |
| 8 | Soil typology (e.g., classification according Eurocodes) | 3.50 | 1.118 | 1 |
| 9 | Level of exposure to snow (according to Eurocodes ) | 2.95 | 0.805 | 0.5 |
| 10 | Class of exposure to wind and terrain category (according to Eurocodes) | 3.19 | 0.602 | 1 |
| 11 | Level of engineering alterations with potential impact on the soil properties (e.g., mines, deforestation, fuel extraction) | 3.57 | 0.746 | 1 |
| 12 | Presence of hazardous industrial areas for potential disaster chain occurrence (e.g., nuclear plants) | 3.86 | 1.014 | 2 |
| 13 | General climatic type according to Köppen classification (e.g., continental, temperate, tropical) | 2.46 | 0.660 | 1 |

Despite the initial disagreement about criteria 8-10 and their consideration as hazard and site-specific, a sufficient agreement and an increase in their scoring was registered over the second round. Criteria 6, 8, 9 and 10 were deemed considerably less relevant in comparison to other indicators, even though it is considered surprising given the impact of those factors on the overall buildings' stability and durability over time. Similarly to what observed in relation to indicator 7, experts pointed out a higher relevant of "local environmental factors" (i.e., 6) and exposure to snow and wind (i.e., criterion 9 and 10) as more impacting in terms of design.

It is however argued that the aforementioned factors have a consistent and steady impact over the whole buildings' service life and that their detrimental effects could be mitigated by means of bespoke maintenance strategies. This is for example the case of pollutants and chlorides which are renowned to have an aggressive impact on structures, for instance increasing the deterioration of steel when close to marine areas or RC structures where the reinforcement is exposed. Following to experts' feedback, an additional indicator was implemented in the second phase, namely the "general climatic type", however a weak agreement was attained relatively to its low importance. A noteworthy consideration can be highlighted in relation to the criterion identifying the potential presence of hazardous areas within or close to the analysed area, namely indicator 12. The scarce importance ascribed to this indicator is rather surprising when thinking about lessons learnt from the Fukushima disaster nuclear catastrophe.

### 4.4.2. Governance & Planning

The current category exhibited a rather low consensus rate over the experts' feedback in the first round, but higher scores and agreement have been achieved in the second stage of the consultation as evidenced by Figure 4.3 and Table 4.8. While certain criteria such as the scale of hazard management strategies registered a strong approval and a high score over the two rounds, others were not deemed as relevant. For instance, the criterion addressing the compliance to regulatory landscape registered an overall weaker consensus and over the second round.



(a) (b)

**Figure 4.3:** Governance & planning boxplots after the first (a) and second (b) rounds of consultation.

Despite this, the comments provided by the experts' were in favour of the consideration of this indicator although its relevant is highly conditional on the existing regulatory frameworks. Given the need for including early warning strategies, indicator 15 was reformulated during the second round in order to embed this also in light of the experts' feedback. The modification allowed to achieve a higher scoring for this indicator even though the standard deviation evidences a certain extent of disagreement. It is argued however that early warning systems play a prominent role in the context of resilience, namely both in terms of prevention and recovery.

**Table 4.8:** Statistical analysis of results for the governance & planning category.

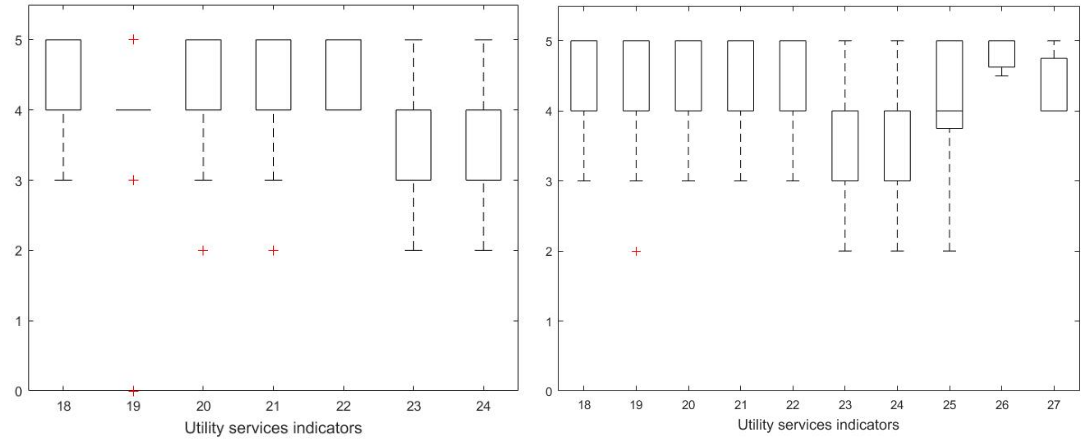
| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 13 | Scale of hazard governance strategy (e.g., flood prevention strategies at local, regional and national level) | 4.61 | 0.739 | 1 |
| 14 | Level of compliance to existing regulatory landscape | 3.86 | 0.640 | 0.75 |
| 15 | Presence of data sensing and acquisition for hazard forecasting | 3.91 | 1.342 | 2 |
| 16 | Education (from elementary or secondary school), training and communication | 4.05 | 0.999 | 1.75 |
| | **Second round** | **Mean** | **St.Dev.** | **IQR*** |
| 14 | Scale of hazard governance strategy for hazard prevention and recovery (i.e., post-disaster reconstruction) | 4.43 | 0.746 | 1 |
| 15 | Effectiveness of previous disaster governance strategies | 4.75 | 0.500 | 0.5 |
| 16 | Level of compliance to existing regulatory landscape | 3.76 | 0.831 | 1 |
| 17 | Presence of monitoring and data collection (i.e., early warning systems) | 4.13 | 1.170 | 1 |

Early warning systems are also key for critical infrastructures maintenance and management in light of hazard prevention. An evident example can provided in relation to landslide-prone gullies, where the implementation of early warning systems can foster the development for more efficient preventive strategies and prompt the evacuation in the occurrence of disaster by informing the population. Following to the experts' feedback, the criterion addressing education and training was removed as deemed as not relevant for the scope of built environment resilience assessment. It is in fact regarded as more influencing when applied to resilience on a broader scale.

### 4.4.3. Utility services

The current category exhibited amongst the most significant improvements from one round to the other, both in relation to the score assigned to the criteria and in terms of compactness of the dataset, as evidenced by Figure 4.4 and Table 4.9. The only criterion that registered a score lower than 4 is the "separation of used water into grey and black flow", concluding the second round with a score of 3.38. It was observed by the experts that cross- contamination of water can dramatically escalate the impact of a hazard at the urban scale.

The results presented in Table 4.5 evidence a successful scoring for the proposed set of criteria, although the "vulnerability of energy supply network" was deemed as the most impacting for resilience and it was assigned a score of 4.83 with great agreement amongst the experts. It is renowned that the prompt detection of faults in the energy supply network can aid recovery processes as the vulnerability of the network gains prominent importance specifically in the aftermath of a disaster.



(a) (b)

**Fig. 4.4:** Utility services boxplots after the first (a) and second (b) rounds of consultation.

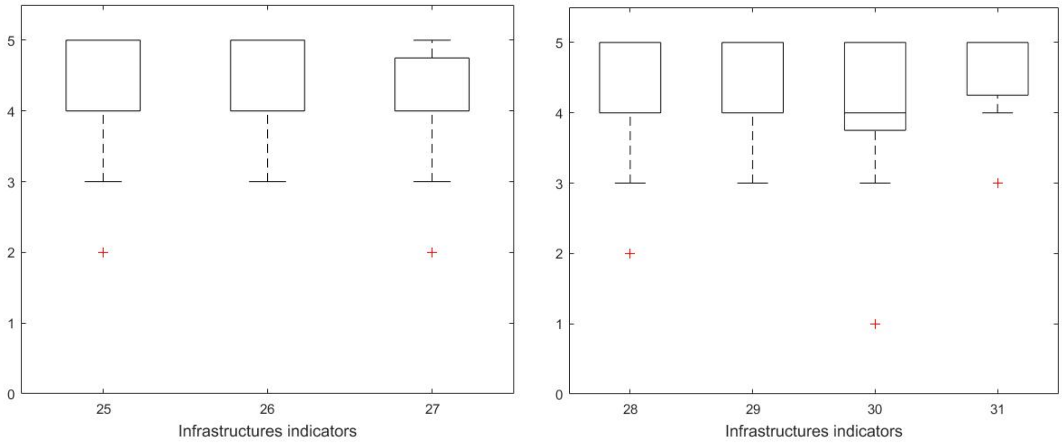
The integration of this criterion was however subsequent to experts' feedback, as well as the "integrity and connectivity of telecommunication and energy supply networks". The latter criterion grounds on the need of relying on a stable communication network able to withstand the effects of a disruption, hence facilitating recovery and rescue processes.

**Table 4.9:** Statistical analysis of results for the utility services category.

| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 17 | Level of energy autonomy (e.g., backup energy sources, stocks of energy) | 4.41 | 0.666 | 1 |
| 18 | Operational system protection (e.g., system relief, circuit breakers) | 4.05 | 0.653 | 0 |
| 19 | Diversification of energy supply (e.g., fuel mix, multi-sourcing, type of generation) | 4.05 | 0.785 | 1 |
| 20 | Level of functional redundancy (i.e., the ability of functionally similar elements to partly or fully substitute for each other) | 4.05 | 0.999 | 1 |
| 21 | Level of water autonomy (e.g., reservoir capacity, water supply network capacity) | 4.59 | 0.503 | 1 |
| 22 | Separation of used water into grey and black flows | 3.41 | 0.908 | 1 |
| 23 | Level of waste water discharge capability (e.g., soil absorption, green or grey infrastructures) | 3.55 | 1.011 | 1 |
| 24 | Diversity and redundancy of telecommunication systems (e.g., cable internet lines, wireless technologies, satellite) | 4.27 | 0.827 | 1 |
| | **Second round** | **Mean** | **St.Dev.** | **IQR*** |
| 18 | Level of energy autonomy (e.g., backup energy sources, stocks of energy) | 4.52 | 0.602 | 1 |
| 19 | Operational system protection (e.g., system relief, circuit breakers) | 4.14 | 0.854 | 1 |
| 20 | Diversification of energy supply (e.g., fuel mix, multi-sourcing, type of generation) | 4.14 | 0.655 | 1 |
| 21 | Level of functional redundancy (i.e., the ability of functionally similar elements to partly or fully substitute for each other) | 4.19 | 0.680 | 1 |
| 22 | Level of water autonomy (e.g., reservoir capacity, water supply network capacity) | 4.43 | 0.598 | 1 |
| 23 | Separation of used water into grey and black flows to avoid cross contamination | 3.38 | 0.740 | 1 |
| 24 | Level of waste water discharge capability (e.g., soil absorption, green or grey infrastructures) | 3.43 | 0.811 | 1 |
| 25 | Diversity and redundancy of telecommunication systems (e.g., cable internet lines, wireless technologies, satellite) | 4.00 | 0.949 | 1.25 |
| 26 | Vulnerability of energy supply network (e.g., gas pipes, water reservoirs) | 4.83 | 0.289 | 0.375 |
| 27 | Integrity and connectivity of telecommunication and energy supply networks | 4.33 | 0.577 | 0.75 |

### 4.4.4. Infrastructures

The current category is one of those sustaining the highest score across the two rounds of consultation, with the lowest score being 3.95 and the highest 4.63. Figure 4.5 and Table 4.10 evidence however a certain level of disagreement towards indicator 30 over the second round, namely addressing the level of maintenance of public infrastructures. Despite an initial weak consensus after the first stage, the experts deemed it as less pertinent for resilience enhancement over the second round, with an IQR of 1.25, the highest of this category. However, as alluded to in previous sections, it is argued that the maintenance regime of critical infrastructures might not have an impact on resilience.



(a) (b)

**Figure 4.5:** Infrastructures boxplots after the first (a) and second (b) rounds of consultation.

**Table 4.10:** Statistical analysis of results for the infrastructures category.

| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 25 | Presence of structural health monitoring systems of critical infrastructures (e.g., reservoirs, dams) | 4.36 | 0.902 | 1 |
| 26 | Connectivity level of transportation networks (e.g., railway stations, airports) | 4.32 | 0.716 | 1 |
| 27 | Level of maintenance regime of public infrastructures | 4.05 | 0.722 | 0.75 |
| | **Second round** | **Mean** | **St.Dev.** | **IQR*** |
| 28 | Presence of structural health monitoring systems of critical infrastructures (e.g., reservoirs, dams) | 4.33 | 0.856 | 1 |
| 29 | Connectivity level of transportation networks (e.g., railway stations, airports) | 4.33 | 0.796 | 1 |
| 30 | Level of maintenance regime of public infrastructures | 3.95 | 0.973 | 1.25 |
| 31 | Accessibility and transport network proximity to emergency services | 4.63 | 0.644 | 0.75 |

It is fact known that structures and infrastructures are subjected to the effects of time and external stressors, hence degradable. Consequently, it is of key importance to preserve their functionality and efficiency in order to ensure a reliable infrastructural network. As a result of the experts' feedbacks, an additional criterion was added in the second round relatively to the "accessibility and transport network proximity to emergency services". This is relevant as the impossibility of accessing a disrupted area would hinder the rescue processes.

### 4.4.5. Emergency & rescue services

As evidenced by the results of the consultation over the two rounds, there has been a consistent agreement amongst the experts in relation to the importance of the indicators pertaining this category. The boxplots in Figure 4.6 exhibit no evident differences both in terms of dispersion of the dataset and scoring of the indicators, as also outlined in Table 4.11. Some experts observed that the availability of contingency plans (i.e., indicator 31) pertains a community perspective of resilience rather than the physical environment one targeted by this research.

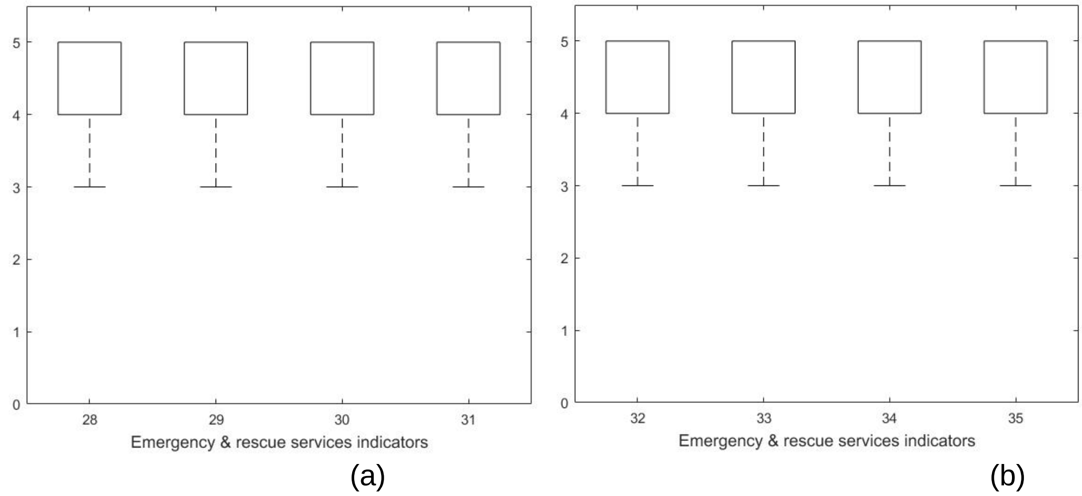


**Figure 4.6:** Emergency & rescue services boxplots after the first (a) and second (b) rounds of consultation.

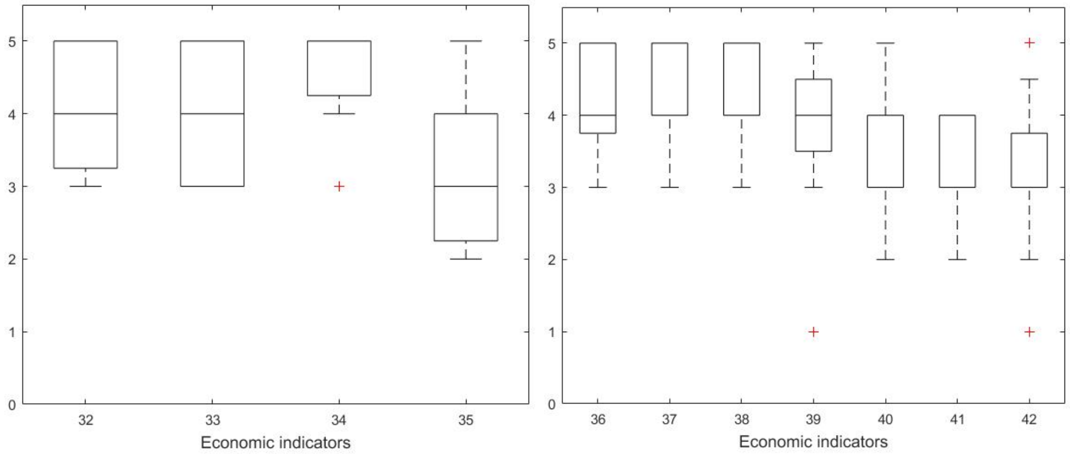
**Table 4.11:** Statistical analysis of results for the emergency&rescue services category.

| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 28 | Redundancy of critical infrastructures (e.g., hospitals) | 4.45 | 0.671 | 1 |
| 29 | Spatial distribution of critical infrastructures | 4.32 | 0.716 | 1 |
| 30 | Emergency communications, access to warning systems and evacuation information | 4.64 | 0.581 | 1 |
| 31 | Availability and update of contingency plans (e.g., evacuation strategies, traffic management) | 4.41 | 0.666 | 1 |
| | **Second round** | **Mean** | **St.Dev.** | **IQR*** |
| 32 | Redundancy of critical infrastructures (e.g., hospitals) | 4.48 | 0.750 | 1 |
| 33 | Spatial distribution of critical infrastructures | 4.24 | 0.700 | 1 |
| 34 | Emergency communications, access to warning systems and evacuation information | 4.52 | 0.680 | 1 |
| 35 | Availability and update of contingency plans (e.g., evacuation strategies, traffic management) | 4.38 | 0.740 | 1 |

It is pertinent to argue this view pointing out the existing correlation amongst the smooth interventions of emergency rescue services and evacuation or traffic management strategies. As an example, if a fire occurs in a urban district, the easier the fire brigade can extinguish it, the better are the chances to avert further damages to a structure and its potential collapse. Both spatial distribution and redundancy of critical infrastructures have been accounted as relevant specifically concerning the post-immediate response and recovery coordination strategies, with a considerable consensus rate amongst the experts.

### 4.4.6. Economy

Following to the consistent lack of consensus achieved after the first round and evidenced by the IQR values in Table 4.12 and grounding on the experts’ advice, the criteria for this category have been consistently reformulated and improved in the second stage of the consultation.



(a) (b)

**Figure 4.7:** Economy category boxplots after the first (a) and second (b) rounds of consultation.

The first three criteria of the first round (i.e., 32-34) registered a rather consistent score between the two rounds even though indicator 33 (i.e., 38 in the second round) exhibited a much better consensus halving from 2 to 1 in terms of IQR. Overall the range of scores for all the criteria remains consistent between the two rounds, ranging between 3.27 and 4.68 over the first stage and amongst 3.21 and 4.62 in the second one.

The relatively low importance of the GDP is deemed as not relevant in both rounds with an increasing level of consensus over the second round. However, it has been previously discussed in this chapter how existing literature evidences that a strong correlation exists between the expected resilience of structure and the financial availability of a specific country. This applies to prevention, maintenance and recovery being resilience comprehensive of all the stages involved in the buildings’ lifecycle.

The experts raised the importance of considering the presence of Non-governmental Organizations (NGO) and the availability of foreign aids to support recovery and consequently this was integrated in the second round of elicitation. However, despite its contribution for resilience, the registered score was not amongst the highest also registering a borderline consensus rate of 1.

**Table 4.12:** Statistical analysis of results for the economic category.

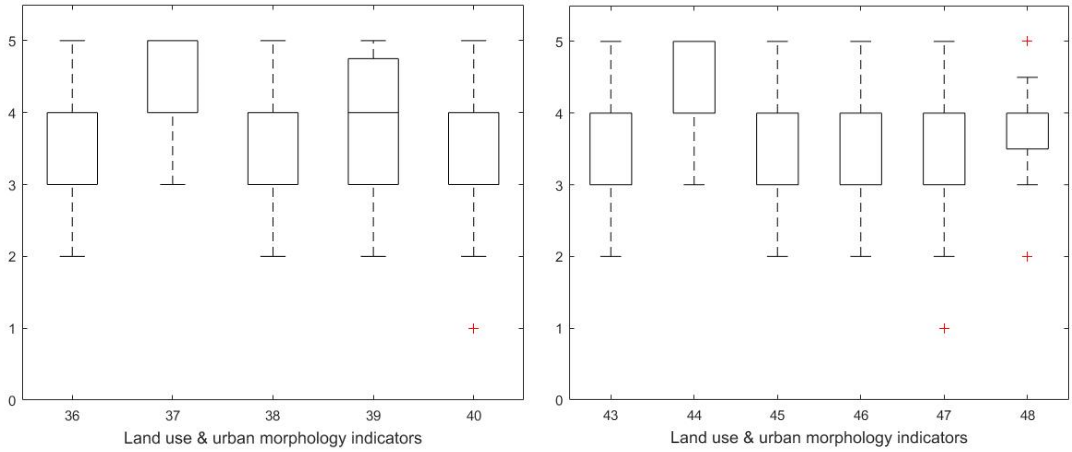
| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 32 | Availability of post-disaster financial assessment | 4.05 | 0.785 | 1.75 |
| 33 | Availability of financial support to comply with existing regulations (e.g., structural interventions to comply to new building regulations) | 3.95 | 0.785 | 2 |
| 34 | Availability of financial support for immediate post-crisis response (e.g., governmental, insurance coverage, contingency funds) | 4.68 | 0.568 | 0.75 |
| 35 | Country Gross Domestic Product (GDP) | 3.27 | 1.032 | 1.75 |
| | **Second round** | **Mean** | **St.Dev.** | **IQR*** |
| 36 | Availability of post-disaster financial assessment | 4.05 | 0.740 | 1.25 |
| 37 | Availability of local financial support to comply with existing regulations (e.g., structural interventions to comply to new building regulations) | 4.12 | 0.705 | 1 |
| 38 | Availability of financial support for immediate post-crisis response (e.g., governmental, insurance coverage, contingency funds) | 4.62 | 0.669 | 1 |
| 39 | Mixture of resources available for post-crisis response (e.g., partly supplied by government, partly underwritten by insurance) | 3.83 | 1.115 | 1 |
| 40 | Country Gross Domestic Product (GDP) and its influence on prevention and recovery | 3.48 | 0.928 | 1 |
| 41 | Presence of NGOs and capability of using foreign aid | 3.42 | 0.793 | 1 |
| 42 | Classification of industrial structures and type that support local economy | 3.21 | 1.157 | 0.75 |

A slightly better importance was assigned to indicator 39, meaning that the experts deemed as more relevant the potential contribution of mixed-source contributions in place rather than potential foreign aids. The least important criterion identified by the experts was the local industrial economic support, which scored 3.21 with however a rather significant dispersion, as visible in Figure 4.7.

### 4.4.7. Land use & urban morphology

The scores assigned to the criteria over the two consultation rounds did not differ significantly, as shown in Table 4.10 and as also visible in the boxplots of Figure 4.8. One indicator was added in the final consultation stage following to the experts' suggestions, namely the one addressing the prevailing land use which however registered a relatively average importance with a consistent agreement.

The majority of the indicators over the second stage of consultation were scored as slightly below 4 with an IQR of 1 for almost all of them. This category was not deemed by the experts as the most influencing for resilience, however the population density appears to have registered a good consensus around its relevance.



(a) (b)

**Figure 4.8:** Land use & urban morphology boxplots after the first (a) and second (b) rounds of consultation.

In contrast to the experts' opinion, indicators such 38, 39 and 40 (i.e., 45, 46 and 47 in the second round) provide a tangible and measurable characterization of the urban topography specifically in relation to the built environment. As outlined in previous sections, the utilization of these indicators enables a more accurate characterization of the urban landscape, not just from a functionality standpoint, but in terms of population density distribution and buildings' elevation across the area. In light of this, it would be easier to quantify and qualify the inherent vulnerability of specific areas in face of hazards. Similar considerations apply to the urban fabric and development pattern criteria, which was deemed not influencing for resilience over both the consultation rounds.

**Table 4.13:** Statistical analysis of results for the land use & urban morphology category.

| | **First round** | **Mean** | **St.Dev.** | **IQR*** |
|---|---|---|---|---|
| 36 | Urban fabric and development pattern | 3.45 | 0.963 | 1 |
| 37 | Population density (i.e., concentration of people per square kilometre) | 4.41 | 0.590 | 1 |
| 38 | Floor area ratio (FAR) on an urban scale (i.e., ratio between the sum of the buildings' floor surfaces and the urban centre area) | 3.68 | 0.839 | 1 |
| 39 | Building coverage ratio (BCR) on an urban scale (i.e., ratio between the sum of building external footprints and the urban area) | 3.68 | 0.945 | 1.75 |
| 40 | Buildings' height profile (e.g., Digital Surface Models techniques) | 3.32 | 0.995 | 1 |
| | **Second round** | **Mean** | **St.Dev.** | **IQR*** |
| 43 | Urban fabric and development pattern | 3.33 | 0.796 | 1 |
| 44 | Population density (i.e., concentration of people per square kilometre) | 4.38 | 0.669 | 1 |
| 45 | Floor area ratio (FAR) on an urban scale (i.e., ratio between the sum of the buildings' floor surfaces and the urban centre area) | 3.71 | 0.845 | 1 |
| 46 | Building coverage ratio (BCR) on an urban scale (i.e., ratio between the sum of building external footprints and the urban area) based on satellite imageries and GIS techniques | 3.69 | 0.814 | 1 |
| 47 | Buildings' height profile (e.g., Digital Surface Models techniques) | 3.52 | 1.167 | 1 |
| 48 | Predominant Land use/type | 3.71 | 0.916 | 0.5 |

### 4.4.8. Termination criteria for the Delphi consultation process

In order to define an univocal criterion to stop the Delphi consultation and in accordance to what explained over Section 4.2, the methodology proposed by Dajani et al. [263] is herein utilized. In this approach, a Delphi consultation can be ended whenever the stability of the responses occurs simultaneously to the consensus target fulfilment. Consensus can be measured as previously outlined in the methodology chapter, while stability consists in the statistical coherency across two responses for the same criteria over two consequential rounds of consultation.

The approach proposed by English and Kernan is adopted [264] with the aim of quantifying stability as also formerly anticipated in the methodology chapter. As previously explained, the authors calculate a Variation Coefficient, resulting from the ratio between each criterion's standard deviation and mean score. The resulting Variation Coefficients for each round were calculated in relation to the proposed criteria and presented in Figure 4.9.

The interruptions of the first round trend line in the graph are motivated by the addition of several indicators over the second stage of consultation, which clearly results in the unavailability of a Variation Coefficient in those points. The x axis represents each criterion by its index as presented in the results section, ranging in fact from 1 to 48. The dotted trend line represents instead the absolute discrepancy between the Variation Coefficients across the two rounds.

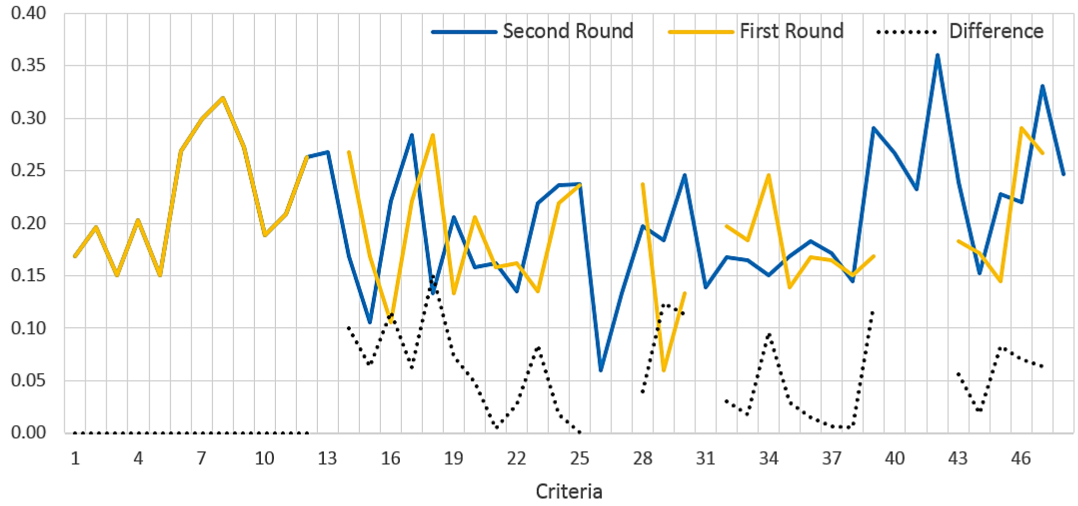


**Figure 4.9:** Variation coefficients for the criteria over the two rounds of consultation.

As outlined in Section 4.2.5, the difference between the Variation Coefficients across subsequent rounds for each indicators is calculated as presented in Figure 4.9. According to English and Kernan, a Variation Coefficient between 0 and 0.5 consists in a sufficient condition for the establishment of consensus and hence enabling the termination of the consultation process. Overall, stability is achieved by the whole data set as evidenced by Figure 4.9.This is evidenced by the dotted line in Figure 4.9 which represents the Variation Coefficient across the assessed indicators. It is evident how the value of the coefficient is significantly below the threshold of 0.5, meaning that consensus is achieved after the second round and the consultation can be stopped.

However, the peak value of 0.151 for the Variation Coefficient is exhibited by the criterion 18 (i.e., 17 in the first round), which identifies the “level of energy autonomy” is the “Utility services” domain. Ultimately, the Variation Coefficient was calculated for just those indicators which were common to both rounds of consultation, as the ones which were added later on in the second state would not have a corresponding criterion in the first round averting the calculation.

## 4.5. Discussion

As a result of the consultation process, the final framework for urban-level resilience is herein proposed as in Figure 4.10. The whole set of the final 48 criteria is distributed across the outer ring of the wind rose diagram, which is also divided according to the seven identified domains. The core portion of the framework represents a global view of the relevance of each criterion following to the expert consultation and in terms of their mean score. Overall, the majority of the indicators were deemed relevant being assigned a score higher than 4, whereas a small portion was rated between 3 and 4.

Following to the analysis of the consultation results as presented in the former section, a solid increase in terms of consensus rate and compactness of the data set was registered from the first to the second round. It has in fact been calculated that the number of satisfactory criteria for each round raised from 30 over 40 in the first stage to 43 over 48 in the second one, with the latter registering an overall consensus of 90%. However, 5 indicators over 48 did not meet the minimum benchmark for the consensus achievement and 2 of them in particular were attributed a score lower than 3 and consequently deemed as not relevant for resilience assessment and enhancement. With respect to the identified dimension to characterize resilience it is pertinent to observe that 2 of them registered an overall satisfactory level of consensus for all the criteria. On the other hand, the unsatisfactory indicators are spread amongst the remaining five categories, with the environment presenting two of them while infrastructure, utility services and economy accounted for just one.

As far as the environmental domain is concerned, the level of exposure to snow and the general climatic type have been regarded as not relevant for the assessment and enhancement of resilience. Grounding on the experts’ feedback provided during both the consultation stages, it has been acknowledged that the disagreement around these criteria stemmed from two main motives: (i) the two proposed criteria entail the consideration of variables which are generally more influencing over the design phase, hence leading to redundancy if accounted for twice, and (ii) a potential overlapping with a hazard assessment, if present. In reply to those meaningful observation and as alluded in section 4.2, indicators from 1 to 10 can be neglected when a hazard assessment for the area were available in order to avert overlapping. Unexpectedly, the indicator entailing the geotechnical awareness was scored relatively low as the experts' position is about this indicator as more impacting for design rather than for resilience. However, the geotechnical awareness does not entail only the soil underneath structures and infrastructures, but it also involves the surroundings, hence including slopes and the terrain properties of the analysed area in general. This is particularly meaningful when dealing with context such as Old Beichuan, where the urban centre lies in a gully surrounded by mountains hence being particularly vulnerable to rock falls and landslides, as the 2008 Wenchuan seismic event proved. The geotechnical awareness of the area therefore accounts for the potential identification of vulnerability hindering the built environment but also the geological surrounding, hence aiding the strategic consideration of vulnerability identification, prevention, monitoring and recovery management.

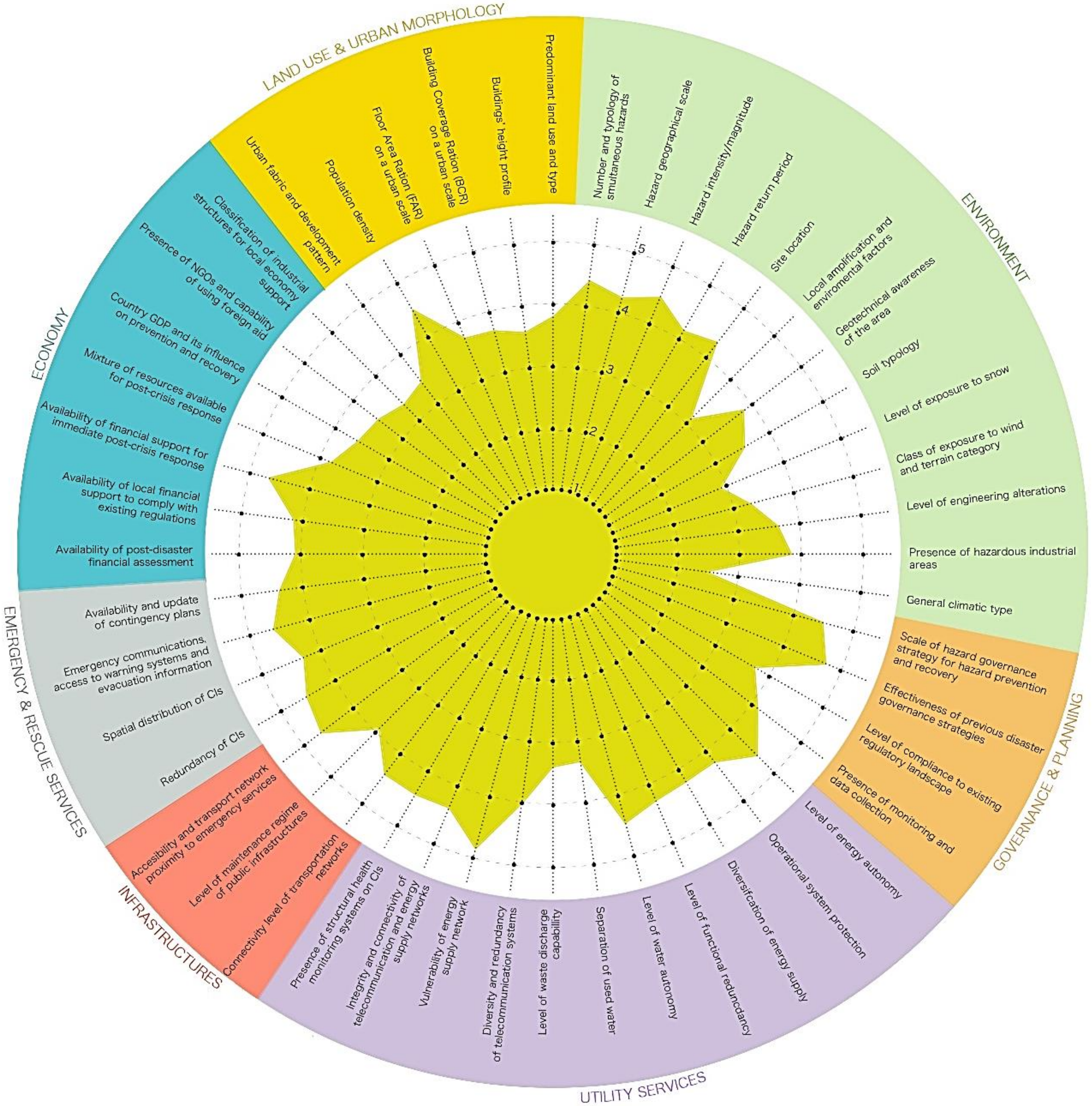


**Figure 4.10:** Final framework for urban-scale resilience assessment.

Another criterion that did not register a high success rate amongst the experts was the presence of hazardous areas in the surroundings of the urban centre, including for instance nuclear power plants. It is noteworthy to mention that the relevance of this criteria is related to the potential occurrence of disaster-chain effects, which often characterizes highly interconnected complex systems, such as urban districts [97]. However, while this indicator was scored as relatively important with 3.77 and an improved consensus rate lowering from 2.75 to 2, the geotechnical awareness criterion halved its consensus moving from an IQR of 1 to 2 from the first to the second consultation round. Overall the main objection moved by the experts in relation to the criteria that would eventually result dissatisfactory was their inadequacy to characterize resilience and being instead more suitable to be implemented just for design purposes.

Similarly to the previous criteria, also the level of maintenance for critical infrastructures ended the consultation process with a dissatisfactory IQR of 1.25 and scoring 3.95. Surprisingly, the level of redundancy of telecommunication systems registered a lower score over the second round with a final assigned importance of 4 and the level of consensus decreased of 0.25 resulting in an IQR of 1.25. As previously discussed in the results section, these results appear as unexpected considering the broad consensus existing in the literature around the relevance of these factors for the resilience of structures and infrastructures in face of hazards.

The indicator addressing the availability of post-disaster financial assessment registered 4.05 at the end of the second round with an IQR of 1.25, representing a non-satisfactory consensus rate. If we compare these results to the work by Alshehri et al. [94] it can be observed that the closest indicator would be the one entailing insurance coverage from hazard occurrence. However in the context of the framework proposed by Alsheri et al. the attained score was 3.75 on an equivalent 5-Likert scale but achieving the consensus. It is therefore pertinent to observe that in terms of recovery and reconstruction policies, the capacity of providing a damage quantification and qualification is of primary importance for insurance coverage [94]. The latter is also regarded as a rather influencing factor for resilience by Da Silva [6]. A prompt damage assessment leading to a financial evaluation would boost the development of recovery plans, consequently aiding the recovery process. On the other hand, it is acknowledged that most private households might be uninsured, however in case of large-scale disasters governments generally provide for inhabitants' accommodations reconstruction and help is often granted by NGOs of international aids. Insurance coverage becomes a prominent factor when dealing with large infrastructures, such as bridges, dykes, hospitals or public-owned buildings.

Regarding the maintenance regime for structures and infrastructures, it is worth mentioning that the existing literature shares large consensus in relation to its importance for resilience enhancement [5, 6]. A pertinent example would be the work devised by Labaka et al. specifically addressing critical infrastructures [81]. It is relevant to mention that in the case of the PEOPLES framework [92, 93] the maintenance of infrastructures is not explicitly accounted for, whereas it is often referred to their functionality and performance before, during and after the disaster occurrence. It is relevant to mention that in the indicator addressing the maintenance regime it was not intended to factor in only its influence on prevention, but also on the structures' robustness. Therefore, being the latter defined as the ability of an element to sustain a performance such not to endanger human lives when subjected to a certain level of stress [65], it is noteworthy how this concept links to the immediate post-disaster structures' response.

## 4.6. Conclusion

Chapter 4 answered research question 1, which is restated as follows:

*Can a disaster management framework be developed to address buildings' resilience at the district level with a holistic consideration of related factors?*

As formerly outlined in the Chapter 3, this is one side of a comprehensive framework for resilience assessment and enhancement which aims at its characterization from a qualitative and quantitative perspective [43]. This chapter namely encompassed the qualitative level, defined as such given the less analytical elaborations required to attain a resilience assessment compared to the methodology proposed for the building-scale approach. The work herein proposed therefore aims at holistically address resilience from a micro (building-level) and macro (district-scale) perspective [43], where the latter is specifically addressed in the current Chapter.

The proposed framework is informed by the extensive review carried out in Chapter 2, where the multi-faceted and interdisciplinary nature of resilience is highlighted. This led to the consideration of a series of frameworks and it has been observed that the shared approach towards a resilience quantification at the macro scale of analysis is facilitated by the consideration of different domains characterizing resilience. However, each of the identified categories has to be broken down and further deconstructed into its featuring criteria so that to facilitate the assessment process and the resilience description. Both the domains and the criteria were identified grounding on a review of frameworks for resilience with both research and non-academic backgrounds in order to ensure a comprehensive approach. Domain specific frameworks were also analysed, quantifying resilience for specific portions of the urban systems, such as critical infrastructures and energy systems. This strategy helped the characterization of the criteria for specific domains.

Following to the identification of the main framework skeleton, a Delphi consultation was carried out as being identified as the most reliable techniques to gather international feedback from domain-specific experts across different subjects. The initial set of indicators involved 43 criteria clustered into 7 categories, but after the experts' feedback analysis 5 criteria were added for a final set of 48 indicators. The domains selected to characterize resilience comprehend environmental, financial, organizational, governmental, infrastructural and urban features. The experts were then tasked to assign a score to the criteria and allowed to provide comments and propose new criteria. Their responses were analysed utilizing statistical indexes such as inter-quartile range, standard deviation and mean.

The results after the second round exhibit a consistent improvement in terms of both consensus rate and experts' opinion compactness, however leaving 5 out of 48 indicators as not satisfactory. The highest rate of disagreement was registered for the environmental category, where 2 unsatisfactory indicators were identified by the experts and deemed not as much relevant for resilience as they would be for design. Even though the experts' feedback was overall very beneficial, come of the categories appeared undergone major improvements across the two rounds of consultation. Grounding on the results presented in the previous section it is possible to observe that perhaps the three domains which benefitted the most from the experts' feedbacks were the economy, utility services and environment. These three clusters appear as the ones undergoing the most significant structural changes between the rounds, as the criteria were fundamentally improved.

Overall, the experts' main comments addressed the unsuitability of considering features not directly part of the built environment system (e.g., soil, weather, local amplification factors or nearby hazardous infrastructures). It is argued however that these represent key factors for a comprehensive resilience assessment, specifically because a building (or a structure in general) cannot just rely on its own features neglecting the surroundings. In fact, the structure's features would define its vulnerability, which would therefore define the exposure when related to the hazard features and the surroundings' properties. As a matter of fact, parameters such as soil typology as well as its mechanical properties determine the potential secondary effects that could affect a structure when subjected to the effects of a main hazard. It is the case, for instance, of a seismically-triggered landslide or a rock fall.

Sometimes secondary effects (e.g., landslides, flow-type slides, tsunamis) could lead to even bigger damages compared to the ones caused by the primary hazard (e.g., earthquake). Furthermore, the classification and identification of the potential vulnerabilities, not only of the physical built environment, but also in relation to the surrounding (e.g., slopes) would foster the adoption of prevention strategies to mitigate the impact of the hazard. As an example, landslides-prone slopes could be consolidated in a series of ways (e.g., piles installations or even by planting trees) once identified the nature of the soil and its likelihood to be affected by seismically-triggered phenomena (e.g., liquefaction). However, this implies a relevant financial-related consideration in relation to the consistent economic impact of those interventions given the often-large scale of the territory subjected to geotechnical measures. It is pertinent to point out that often reconstruction costs due to poor prevention greatly overcome those addressing the pursue of mitigation strategies, hence acting in a forward-looking manner would benefit recovery both in terms of time and costs.

Furthermore, the inclusion of feedbacks represents an advantage as the criteria are validated relying on a network of renowned experts providing different and enriching point of views. To this respect, gathering experts from multi-disciplinary backgrounds allows to include aspects that might not have been accounted for initially, for example in this case the international aid provided by NGOs or the consideration of proximity to emergency services.

The advantage of such an approach targeting a specific domain (i.e., built environment), but considerate of context-related features, lies in the adoption of a holistic strategy for resilience assessment which is line with its nature. Similar frameworks attempting cover broadly resilience under the effects of general threats often lack of practicality and applicability. In fact, the scale of analysis becomes so broad to sometimes lose the connection with the object of the resilience assessment.

In light of the above, Chapter 4 answered successfully the posited research question given the consideration of a series of domain related to the built environment’s resilience and therefore the proposed framework is an effective solution for the problem of disaster resilience assessment at the district-level.

# 5. Building-Level resilience assessment and optimization

The literature review discussed and presented in Chapter 2 highlighted how current building-scale approaches tend to over-constrain the research objective, resulting in a scattered and fragmented body of knowledge. The current Chapter will propose an optimized performance-based approach for investigation, damage assessment and forecasting for seismic hazards on masonry infilled Reinforced Concrete (RC) structures. The presented work will be then applied to a building identified in the context of field investigations carried out for the purpose of REACH and adopting the 2008 Wenchuan Earthquake a case-study hazard. The final results in terms of damage reduction will be then compared to the effective attained disruption in order to evaluate the benefits of the proposed approach.

## 5.1. Revisiting research questions

As described in Chapter 3, the building-scale approach entails the consideration of 3 further research stages which will respectively address the following research questions:

- Stage 1 will answer research question 2: *How can structural design parameters be inferred to accurately characterise and model a seismically compromised building in case of limited access to data and lack of supporting documentation?*
- Stage 2 will address research question 3: *Can the governing variables most sensitive to the structural integrity of a building be inferred taking into account a wide range of considerations, including local environmental and geotechnical conditions?*
- Stage 3 will aim at resolving the issue posed by research question 4: *Can these sensitive variables inform the development of less computationally demanding structural analysis models with a view to optimize the structural design of a building?*

To tackle these questions, a real structure is adopted from the site of Old Beichuan in the Wenchuan Province in China. An initial characterization of the building is provided, which is functional for the development of the structural parametric model. Rich photographic material reliably allowed a move from 3D laser scanning point cloud data to architectural semantic building model. From a structural perspective, the main objective is to reduce as much as possible burdensome and repetitive calculations and to attain this, a 3-stage methodology is adopted to optimize and automate investigation, damage assessment and forecasting in infilled RC structures.

As will be extensively explained in the following sections, the aforementioned research stages will adopt different technologies and approaches, featuring an increasing level of abstraction and ultimately detaching from the simulation software to perform damage forecasting.

## 5.2. Methodology overview

The current section outlines the research work addressing an augmented resilience enhancement optimization at the building level through the adoption of deep learning techniques. As formerly outlined in this chapter, the proposed framework articulates into two main approaches namely addressing two corresponding scales of analysis. In the previous section, the district-level approach (i.e., macro-scale) was presented, while this section will introduce the underpinning methodology adopted for the building-level (i.e., micro-scale) resilience assessment.

The methodology adopted for this research thread and as presented in Figure 5.1 starts with a preliminary knowledge acquisition of the building object of analysis, which is needed to inform the semantic model of the structure. As often experienced in practice when investigating a structure and it features, there might be factors hindering the data acquisition. This might be due to the impossibility of accessing the building, hence carrying out direct measurements, while in some cases the documentation is not available, or its consultation is not allowed. To overcome these obstacles, the proposed methodology aims at bridging the lack of data occurrence through the application of artificial intelligence techniques to infer the value of certain parameters but also to perform data forecasting. This would allow to replace repetitive iterative calculations necessary to attain the value of the unknown variables through an often-employed trial-and-error approach. As outlined in Figure 5.1 the methodology articulates in the following stages:

- Stage 1: Investigation of unknown parameters;
- Stage 2: Sensitivity analysis;
- Stage 3: Deployment of a combined ANN-GA engine to replace the simulation tool.

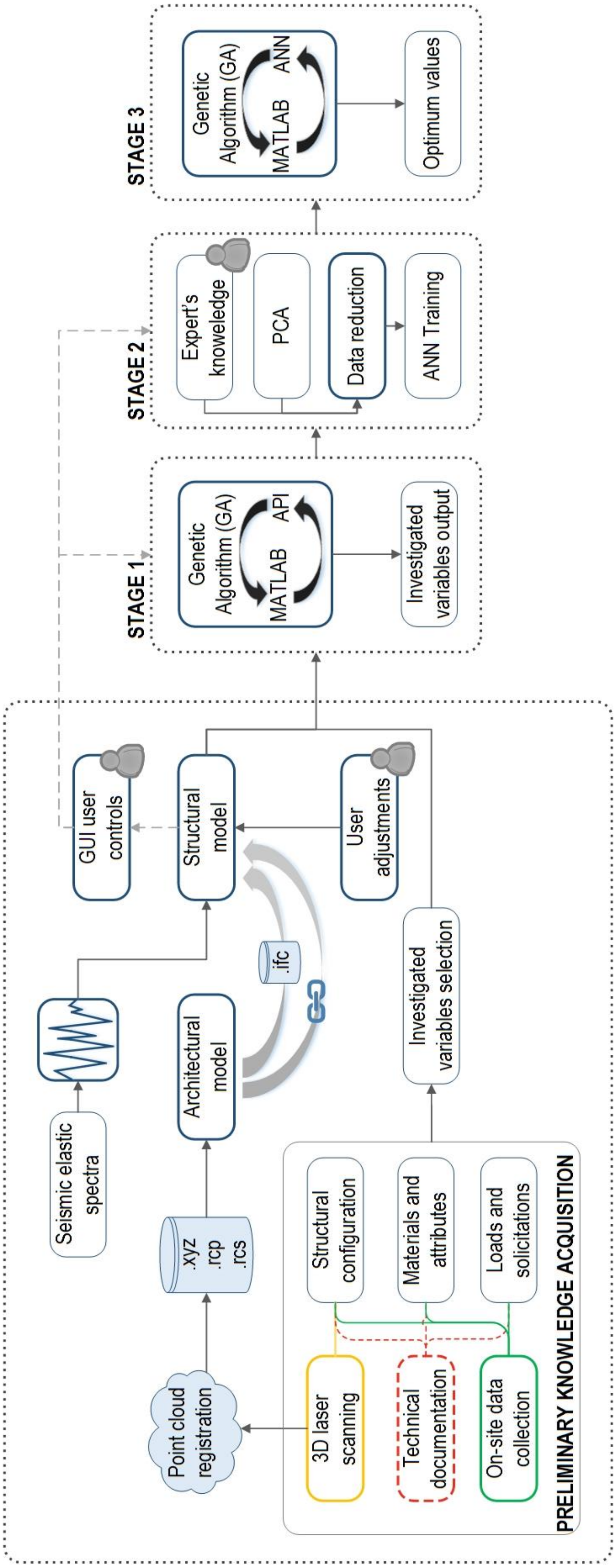


**Figure 5.1**: Quantitative framework methodology schematic.

Clearly, not all the three stages need to be carried out for each analysis. In the occurrence of a reliable level of knowledge of the structure it could be possible to just address Stages 2 and 3. On the contrary, if it is not intended to perform any damage-forecasting analysis it is still possible to just perform Stage 1 and fetch the values for the designated variables as it will be further outlined in the ensuing sections. Given the evidence-based of the proposed approach it is considered pertinent to summarize the nature of the data utilized herein:

- Displacement time-series of the Wenchuan seismic event (source: IRIS, Wilber 3 database);
- 3D point-cloud data;
- Photographic material and on-site observations gathered during two field trips;
- Satellite imagery (source: Landsat/Copernicus and DigitalGlobe).

The proposed methodology is also validated on a building from the site of Old Beichuan, which is located in the Wenchuan County in China. The area was subjected to the devastating effects of the 2008 Wenchuan earthquake and to this regard a diagnostic of the governing failure mechanism exhibited by the building as well as a structural characterization are provided in following subsection. As part of the preliminary data collection and elaboration phases, an on-site 3D laser scanning campaign was performed to acquire a high-resolution point cloud data set which was then registered and imported in the architectural/BIM modelling tool[1] as displayed in Figure 5.1. In order to ensure a solid ground for the ensuing tasks, it is made the hypothesis of considering the geometric representation of the building attained through point-cloud data as reliable. Additionally, it is relevant to highlight that the proposed methodology addresses the superstructure of the building, although future work could entail a further inclusion of the foundation system.

Once the parametric model is realized, its translation into structural model is straightforward and it can be attained either through exploitation of the predefined interlinkage between the structural[2] and architectural modelling tools or simply by adopting and .ifc format extension. However, local adjustments might be operated in relation to the structural model where for instance specific constraints need to be applied or in the occurrence of sections that might not be acknowledged through the transition between the two software. Simultaneously to the other tasks and in order to realistically represent the seismic action, displacement time series were collected

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[1] The architectural/BIM modelling tool employed for this research is Autodesk Revit

[2] The structural modelling tool employed for this research is Autodesk Robot Structural Analysis Professional

from the IRIS online database by means of the Wilber 3 tool and adopting the methodology proposed by Wang [241] and which has been already illustrated in Chapter 3.

## 5.3. Case study building characterization

### 5.3.1. Structural failure appraisal and characterization of Beichuan Hotel

Prior to any numerical assessment, it is vital to conduct a qualitative appraisal of the building in order to characterize it from a twofold perspective. The first objective would entail highlighting its constituting features, such as structural typology, configuration and materials. On the other side, a diagnostic appraisal must be carried out to identify potential design flaws as well as the failure mechanism. The analysis is carried out adopting a top-down approach, therefore moving from the building location and the investigation of the regulatory framework adopted for the design, scaling then down to the structural features and failure mechanism appraisal.

The building adopted to validate the methodology underpinning the proposed research is a leisure infrastructure located in Old Beichuan County, in Wenchuan, China. The Beichuan Hotel namely consists in a masonry-infilled reinforced concrete frame structure located in the southern area of Old Beichuan, as shown in Figure 5.2b. The two satellite imageries depict the district of Old Beichuan in 2001 and 2010, hence before and the after the 2008 seismic event.


(a) (b)

**Figure 5.2**: Satellite imagery of Old Beichuan (squared in red) in 2001 (a) and 2008 after the seismic event (b). [source: Google Earth, Landsat/Copernicus and DigitalGlobe]

Namely, Figure 5.2a allows to infer that the Beichuan Hotel structures had not yet been realized, whereas in the 2010 imagery the roof appears clearly visible. This temporally locates the building construction between the two dates and therefore the regulatory framework adopted for the design is identified in the GB 50011-2001 [290] as the following regulatory update in terms of seismic provision would take place just I 2010, with the GB 50010-2010.

Figure 5.2a provides instead an aerial view of the Beichuan Hotel which is consistent with the satellite imagery of 2010 as shown in Figure 5.2b. The latter represents in fact the area squared in Figure 5.2b which leads clearly shows that the analysed building is not just constituted by the rectangular-shape block as it would erroneously appear from the satellite imagery only. A 3-dimensional view, such as the one of Figure 5.3a leads to two main observations:

- The analysed building has always been structurally disconnected by the pitched-roof structure;
- The collapsed slab almost covered by the trees proves the presence of an additional block, which is also confirmed by a close look at the satellite imagery in Figure 5.3b.

(a) (b)

**Figure 5.3**: Aerial picture of Old Beichuan in 2017 (a) [source: http://www.globaltimes.cn/galleries/840.html], close-up of 2010 satellite imagery with detail of Beichuan Hotel (b), [source: Google Earth].

Two field works were conducted respectively in December 2016 and July 2017 in order to perform data collection and 3D laser scanning which would subsequently inform the digital representation of buildings. Figures 5.4a and 5.4b respectively provide an overview of the current condition of the structure and the semantic model attained in Autodesk Revit based on point-cloud data based on the conducted on-site data collection. The choice of this building over others in the Old Beichuan district is motivated by the failure mechanism which entails merely the superstructure, which is what the proposed methodology aims at investigating.

In light of the above and thanks to the combination of 2-dimensional satellite imagery and 3-dimensional representations provided by the photographic material, a precise characterisation of the building is attainable. The building is therefore featured by a "T-shaped" in-plan configuration with different elevations. Namely, the 1-storey block accommodates the garages, whereas the remaining portion is mainly destined to reception services. Overall, masonry-infill walls are adopted in the structure but in most cases these appear to be just partial as a wide relevance is given to windowed surface, as it can be ascertained from Figure 5.4.

(a) (b)

**Figure 5.4**: Beichuan Hotel, as-built configuration as per site investigation in December 2016 (a) and point cloud data (b). [source: authors].

Figure 5.5 shows in fact that the building's façades are featured by a consistent area percentage of windows and very limited infilled surfaces. This has a twofold implication:

- Reducing the effective columns' length leads to a higher rigidity, hence to a more consistent stress percentage absorbed by the structural element given the positive correlation between the two;
- A poorly-infilled façade, especially at the lower levels of a reinforced concrete frame, often induces to soft-storey phenomena as abundantly also observed in the Old Beichuan district.

The presence of significantly different elevations in addition to an irregular in-plan configuration resulted in the evident torsional mechanism which main rotation nodes occur to be located in correspondence of the junction between the garage block and the reception one. On a general basis, torsional mechanisms derive from the non-coincidence of the mass and stiffness centres in the building configuration. This consequently leads to a moment as the forces applied in the two centres represent a torque, which is calculated as the product between the modulus of the force and the distance between the points of application (i.e., centre of mass and stiffness).

Reasonably, the larger the relative distance between the application points, the greater the torque and hence torsional actions.

(a) (b)

**Figure 5.5**: Photographic material regarding Beichuan Hotel, as-built configuration as to December 2016 field trip with detail of façade (a) and masonry infills (b).

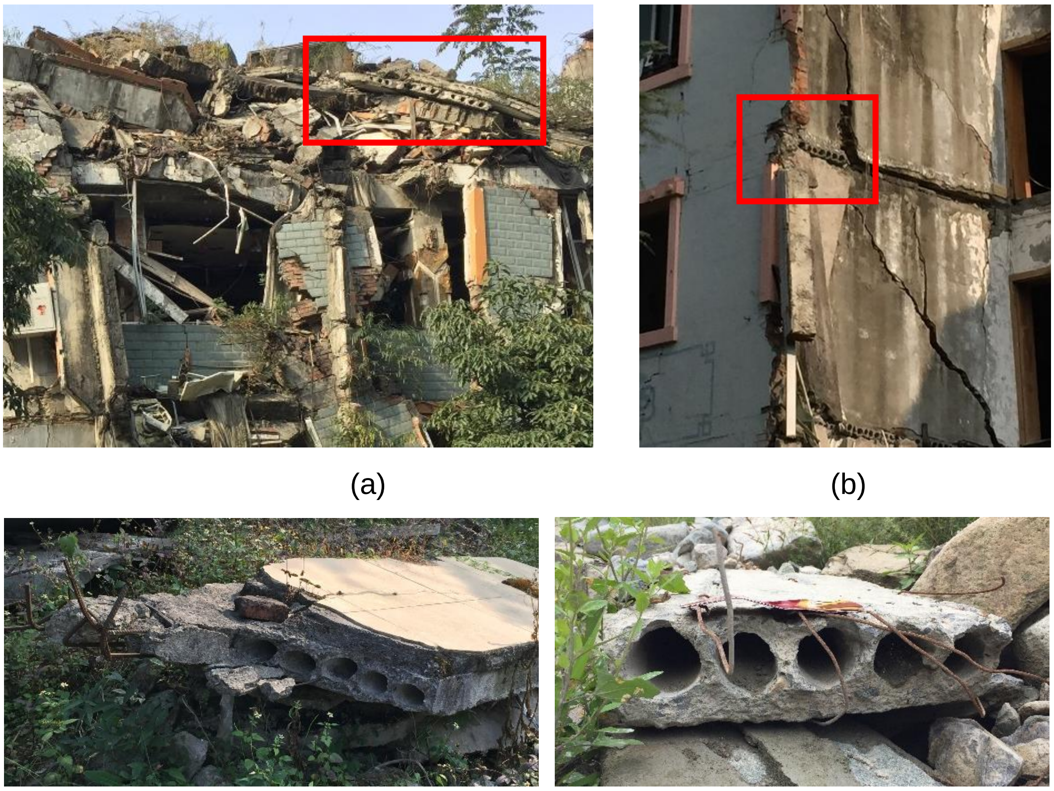
An additional factor that contributed to the overall structural failure is identified in the significant disproportion between the columns' and beams' inertia, which is a result of the section geometry. Given the significantly bigger sections of beams compared to columns, as evidenced by field investigations and point cloud data, the horizontal seismic action was amplified by the inertia of the beams in their plane. As a result, the shear actions on the columns deriving from the seismic acceleration was amplified by the beams' inertia exceeding the shear capacity of vertical elements. In this case, as evidenced by Figure 5.5a, the failure occurred in the node, which did not provide enough shear resistance against the action.

Ultimately, on-site investigations also enabled the collection of reinforcement-related data with respect to the corner columns that will be further characterized in the methodology and results sections. As a result, it was evidenced the employment of 12φ12 for longitudinal reinforcement and 2-arms stirrups with a diameter φ8.

### 5.3.2. Characterization of slab elements

In terms of structural features, it is of interest to identify the typology of slabs and masonry adopted, as their external geometry is provided by the point cloud data, but their mechanical features and section properties cannot be fetched from the site investigation alone. An additional obstacle hindering the building investigation is the lack of access to documentation regarding the structure. Therefore, the photographic material and site-analysis have been of primary importance given that it is possible to gather relevant information by examining at which solutions have been adopted in relation to other buildings. For buildings with analogous functionality, structural typology and configuration, it is very likely that a similarity in features might occur, for instance in the sense of precast slab typology adopted. In fact, construction solutions and techniques are time and context specific.

As an example, throughout the field investigations several sites were examined as well as buildings that have been damaged directly by the 2008 seismic action of indirectly by side phenomena such as rock falls and landslides. However, the same typology of castellated slab has been found both in Qipan and in a series of building in Old Beichuan, as shown in Figure 5.6. Figure 5.6c-5.6d present some examples of buildings where the slab panel has been evidenced in the debris, while it appears as still integrated in the remains of the structures Figure 5.6a-5.6b. Given the impossibility of accessing the debris area in Old Beichuan for security reasons and being instead the slab element in Qipan completely accessible, it has been measured and characterised in order to allow all the further necessary calculations as shown below. The section details are provided in Figure 5.7.



(a) (b)

(c) (d)

**Figure 5.6**: Precast castellated slab panelin Old Beichuan district (a-c) and Qipan gully (d) located during the site investigation.

Considering the prevailing residential functionality of buildings where this typology of castellated slab panels has been detected, a deformability verification has been carried out hypothesising a static load application based on the GB 50011-2001 regulatory prescriptions. An overall section for the slab has also been defined in order to realistically define the loads and conduct the verification, as previously displayed in Figure 5.7. Grounding on point-cloud data and semantic model, the effective slab length *l* has been ascertained to be 6.70 m and the deflection limitation $d_{max}$ to static permanent load application was conservatively taken as shown in Equation 5.1 with a coefficient of 1/250. This poses a maximum deflection of 2.68 cm.

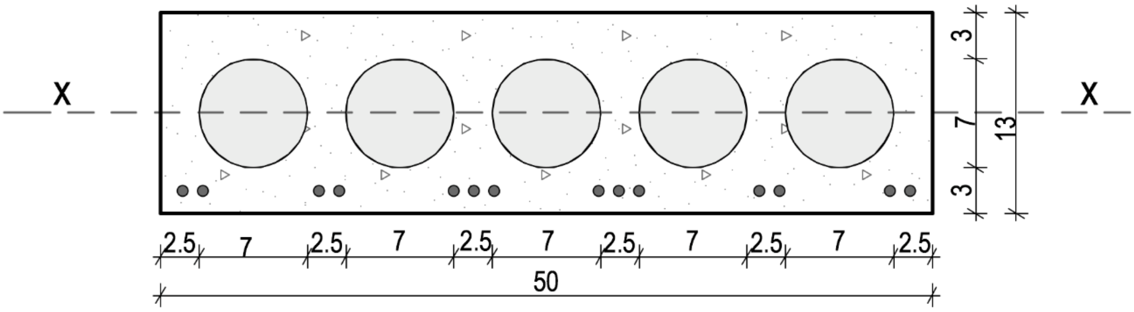


**Figure 5.7**: Castellated slab section.

This formulation has been adopted in place of a precise calculation taking instead into account the realistic features, as a rule-of-thumb methodology is the most likely to have been employed during a pre-sizing stage of the slab. Given that this step aims at simulating the suitability of the surveyed panel for its adoption in the case study building, it is here attempted to simulate the design strategy adopted for the slab elements.

$$d_{max} = \frac{1}{250} l = \frac{670}{250} = 2.68\ cm$$

**Equation 5.1**: Calculation of maximum deflection for slab.

In light of the above, a one span-slab with uniform distributed is considered as a structural scheme for calculation of the effective deflection $d_e$ as shown in Equation 5.2. Instead of 5/384 as for pinned nodes, a conservative 3/384 is taken assuming an intermediate condition between pinned and fixed constrain, namely semi-encastre. This constraint provides a vertical reaction to shear as in a pinned constraint, but also a partial reaction to rotation and consequently there is moment at the supports. The reason behind the adoption of such coefficient for deflection calculation lies in the consideration of a real constraint condition [291], rather than ideal (e.g., pinned, fixed).

Considering that each slab element presents a width of 50 cm, 2 panels are considered for each m of width in the verification. The total load q applied to the slab is calculated as in Equation 3.5a-3.5b according to the prescribed load combinations in the Chinese regulatory framework GB 50009-2001. This regulatory framework also informed the material mechanical properties in terms of density and specifications regarding the load analysis, which is presented in Table 5.1 with respect to the slabs of the first and second floors.

$$d_e = \frac{4}{384}\frac{q*l^4}{E*J} = \frac{4}{384}\frac{(q_a+q_p)*l^4}{E*J} = 1.92 \text{ cm}$$

**Equation 5.2**: Calculation of the effective deflection for slab.

Partition walls are accounted for a conservative value of 2 KN/m$^2$ following to the prescriptions of GB 50009-2001, and they are not considered flexible given the functionality of the storey. Installation and piping is taken also as a conservative value of 150 kg/m$^2$ (i.e., 0.15 KN/m$^2$), while the load of the castellated slab panel is calculated based on the section in Figure 5.2 and specifically in Equation 5.3.

The total section area corresponds to the effective concrete area, which is calculated simply subtracting the empty portions $A_{circle}$ to the rectangular area $A_{rect}$. In order to consider an applied load per square meter, an area $A_l$ corresponding to 1m*1m was taken, hence the corresponding weight for 2 panels was considered on an area of 1m$^2$. The concrete density $D_c$ was considered as a standard of 25 KN/m$^3$ and the resulting distributed load results 2.27 KN/m$^2$.

**Table 5.1:** Load analysis for first and second floors slabs.

| Layer | Thickness (m) | Density (KN/m$^3$) | Load (KN/m$^2$) |
|---|---|---|---|
| **PERMANENT STRUCTURAL LOADS (PS)** | | | |
| Castellated slab panel | - | - | 2.27 |
| Upper screed | 0.08 | 18 | 1.44 |
| | | TOTAL (KN/m$^2$) | 3.71 |
| **PERMANENT NON-STRUCTURAL LOADS (PNS)** | | | |
| Ceramic tiles | 0.02 | - | 0.55 |
| Installations and piping | - | - | 0.15 |
| Partition walls (clay semi-hollow non-bearing walls) | - | 12.5 | 2 |
| Counter ceiling (plywood) | - | - | 0.18 |
| | | TOTAL (KN/m$^2$) | 2.88 |
| **LIVE LOADS (LL)** | | | |
| Canteen Hall | | | 2.5 |
| | | TOTAL (KN/m$^2$) | 2.5 |

Equation 5.4 and Table 5.2 show how the final values for the loads applied on the first and second storey floors in particular after the application of the pertinent coefficients according to the GB 50009-2001 regulatory standards. The final value of 10.64 KN/m$^2$ has to be considered for the final calculation of the slab deflection verification as previously discussed.

$$W_p = 2 * A_s * \ D_c * A_l = 2 * (A_{rect} - 5 * A_{circle}) * 25 * 1 = 2.27\ KN/m^2$$

**Equation 5.3**: Calculation of permanent (a) and live (b) loads.

$$q_p = q_p * \ \gamma = q_p * 1{,}35 \qquad \text{(a)}$$
$$q_a = q_a * \ \gamma * \psi = q_a * 1{,}4 * 0{,}5 \qquad \text{(b)}$$

**Equation 5.4**: Calculation of permanent (a) and live (b) loads.

**Table 5.2:** Application of coefficient for final load calculation.

| Load (KN/m²) | | Coefficient | | TOTAL (KN/m²) |
|---|---|---|---|---|
| | | γ | ψ | |
| PS+PNS | 6.59 | 1.35 | - | 8.89 |
| LL | 2.50 | 1.4 | 0.5 | 1.75 |
| | | | **TOTAL LOAD (KN/m²)** | **10.64** |

The last two elements that have to be characterised in order to calculate the slab deflection consist in the second area moment *J* and the Young modulus *E*. Assuming that a concrete class of cylindrical resistance $f_{ck}$ of 25 N/mm² is taken, an approximate value of the Young modulus $E_c$ can be assumed equal to $5700 * \sqrt{R_{ck}}$ therefore 31.1*10³ N/mm². With respect to steel, the Young modulus $E_s$ is instead taken equal to 2.1*10⁵ N/mm². Given that the homogenization coefficient *n* is given by the ration between $E_c$ and $E_s$, the value of 7 is taken.

The second area for elements presenting void is calculated simply considering the effective section excluding the empty portions. It has to be pointed out that because the load is applied according to the y-axis, the second area moment is calculated according to the orthogonal one, hence x, as also shown in Figure 5.7 and 5.8. It has also been assumed based on on-site investigations and observations on nearby buildings, a 10 cm thick screed is considered upon the structural slab. In order to take into account the reinforcement, its contribution is factored into the second area moment as shown in Equation 5.7.

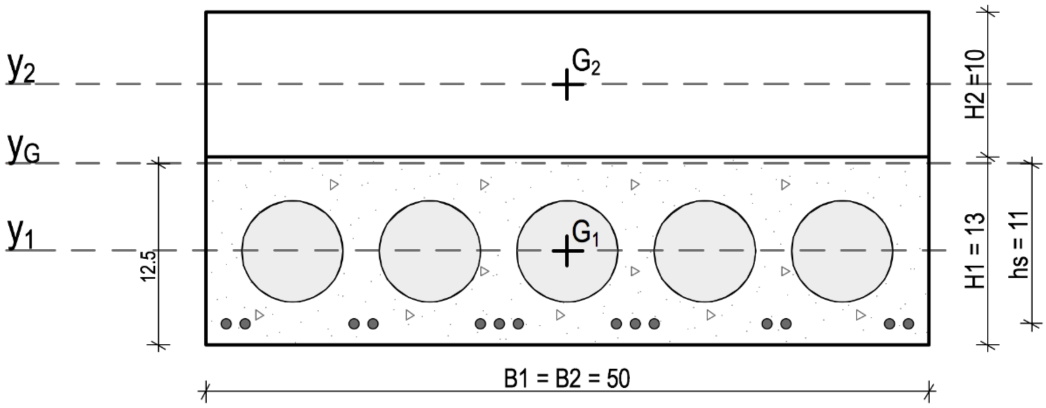


**Figure 5.8**: Castellated slab and upper screed sections with details of axes for second area moments calculation.

$$J_{1,y1} = \frac{B*{H_1}^3}{12} - 5*\frac{\pi*D^4}{64} \quad \text{(a)} \qquad J_{1,G} = J_{1,y1} + (B*H_1 - 5*\pi*R^2)*(y_1 - y_G)^2 \quad \text{(b)}$$

**Equation 5.5**: Calculation of second area moment for slab panel according to barycentre axis (a) and overall slab section barycentre (b).

$$J_{2,y2} = \frac{B*{H_2}^3}{12} \quad \text{(a)} \qquad J_{2,G} = J_{2,y2} + (B*H_2)*(y_2 - y_G)^2 \quad \text{(b)}$$

**Equation 5.6**: Calculation of second area moment for screed relatively to barycentre axis (a) and overall slab section barycentre (b).

$$J_{tot,G} = J_{1,G} + J_{2,G} + n \cdot A_s \cdot h_s^2$$

**Equation 5.7:** Calculation of total inertia for the floor section.

Equations 5.5a and 5.6a present the calculation of the second area moment respectively of the castellated slab and concrete screed respect to their own barycentre axes. However, as visible in Figure 5.8, the overall barycentre axis $y_G$ has to be calculated as the mean between the screed (i.e., $y_1$) and the slab panel (i.e, $y_1$) ones. Consequently, applying Huygens-Steiner Theorem as in Equations 5.5b and 5.6b it is possible to calculate the second area moment respect to the barycentre axis. The resulting inertia of the overall section is simply the sum of the second area moments for the slab panel $J_{1,G}$ and concrete screed $J_{2,G}$ calculated respect to the barycentre overall section as in Equation 5.7.

(a) (b)

**Figure 5.9**: Masonry infill details for police station building in Old Beichuan (a) and virtual representation (b).

The final deflection of the slab $d_e$ resulting from the calculation outline above corresponds to 1.92 cm which is inferior than $d_{max}$ and therefore confirming the suitability of the surveyed slab panel and its integration into the Beichuan Hotel model.

With respect to masonry infills investigations and similarly to the slabs, an investigation on nearby buildings with a corresponding technology has been carried out. It was possible to acknowledge from field investigation on the Beichuan Hotel building that semi hollow blocks were adopted as well as standard UNI bricks for the base layer. Figure 5.9a shown the Old Beichuan police station building, where the same infill technology as in Beichuan Hotel was adopted, resulting however of easier investigation as the infills were completely exposed. Thanks to the accessibility of these information, a virtual representation of the masonry infills was attained as in Figure 5.9b.

### 5.3.3. Characterization of masonry infills elements

As a result of the literature review and particularly grounding on what has been presented in section 2.6.2, a macro-model technique for the semantic representation of masonry infill walls is adopted. In addition to that and in order to order to provide a realistic representation of the building the bespoke strut elements are positioned in order to form a St. Andrew’s cross as recommended by Dolce [227]. Bi-directional struts for masonry infills modelling have also been adopted by O’Reilly in their seismic assessment of school buildings in Italy [224].

The struts’ features are calculated according to Equation 5.8 following the approach by Stafford Smith and Carter [223], grounding on the previous work by Stafford Smith in 1966 [226]. The product $\lambda H$ represents the relative infill to frame stiffness while $E_m$ and $E_c$ respectively represent the Young modules of masonry and concrete for the infill and the frame. $I$ stands for the second area moment of the column while $t$ and $\vartheta$ represent the thickness of the infill and the angle of the diagonal to horizontal. Equation 5.9 allows instead to attain the section geometry $a$ for each strut and according to the work by Mainstone [292] and where $D$ represents the diagonal length between two opposite nodes of the masonry infills.

$$\lambda H = \sqrt[4]{\left[\frac{E_m \cdot t \cdot \sin 2\vartheta}{4 \cdot E_c \cdot I_{col} \cdot h}\right]}$$

**Equation 5.8:** Stafford Smith and Carter mathematical model for relative infill frame stiffness [223].

$$\mathrm{a} = 0.175 \cdot \mathrm{D}(\lambda H)^{-0.4}$$

**Equation 5.9:** Calculation of struts' section based on Mainstone formulation [292].

Therefore, each of the elements is characterized by half of the stiffness of the single model developed by Stafford-Smith and this is achieved by dividing the height of the element in half (i.e., a). The elastic and shear moduli do not require change, consisting in a feature of the material. The methodology proposed by Stafford Smith is used to characterize the strut geometrically in all its features and the Young Modulus of both concrete and masonry are functional to define the section of the strut. On the other side, the material defined in Robot and used to model the struts is masonry, and its parameters have been identified as follows:

- $f_k$ (compressive characteristic resistance of masonry): experimental trials [293];
- E (Young modulus): calculated according to Equation 5.10a in absence of detailed data and in accordance to Eurocode 6 [294];
- G (shear resistance modulus): calculated as in Equation 5.10a and in accordance to Eurocode 6 [294];

$$\mathrm{E}_m = 1000 \cdot f_k \quad \text{(a)} \qquad\qquad G = 0.4 \cdot E_m \quad \text{(b)}$$

**Equation 5.10:** Calculation of elastic (a) and shear (b) moduli for masonry [294].

It is important to distinguish between the simple block element and masonry, since the latter is constituted by the assembled blocks and the mortar. It is acknowledged that the lack of detailed information regarding the mechanical properties of the masonry might lead to errors. However, given the low incidence of masonry in the context of this building it is maintained that the behaviour of the building will not be significantly affected.

It is not possible to hypothesise the mechanical properties of masonry elements given their reliance of in situ tests. In fact, normal practice requires testing the masonry of the building itself in order to acquire relevant properties or at least being able to refer to reliable documentation able to provide information in regard to employed materials. On the other hand, in this particular context none of these two options has resulted to be viable and therefore the most pertinent documentation has been found in an experimental testing of hollow masonry blocks in an existing building context [293]. The blocks present almost equal geometrical characteristics with the ones in Beichuan Hotel, although it is allowed a certain level of uncertainty given the possibly different manufacturing processes that the two types of blocks have undergone. The authors of the test also provided a hypothetical value for a masonry wall adopting the previously tested blocks providing then a rough estimation of the elastic properties of a panel with those features.

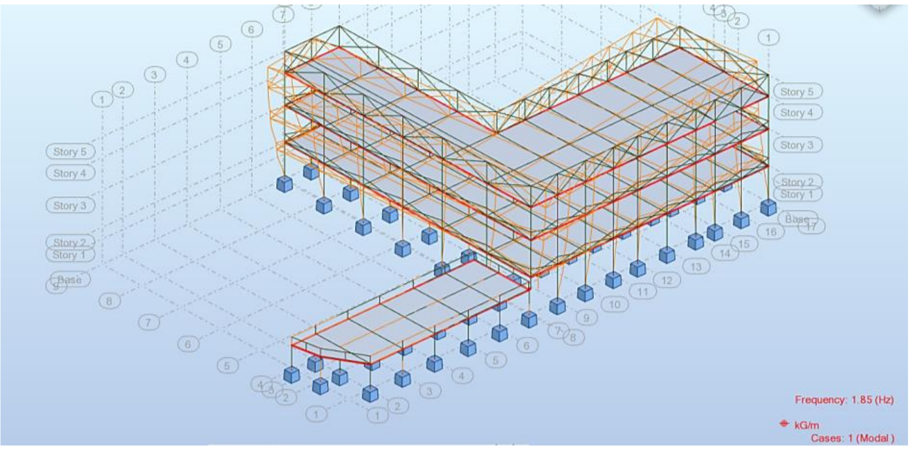


**Figure 5.10**: Structural representation of Beichuan Hotel. [source: author].

Robot does not allow to build structural elements with materials defined by user apart from timber, aluminium, concrete and steel. Consequently, the material Aluminium has been modified with masonry properties in order to make it selectable for the definition of bars. Additionally, in order to define the bar, the sections have been defined as parametric solid, each of them characterized by half of the height according to Stafford Smith and a width (i.e. t) corresponding to the one of the infill. Material density has also been set to zero given the need for applying the masonry load separately on the underlying beam.

As a result of the building characterization, Figure 5.10 shows the structural model overlapped by the first mode resulting from the modal analysis as described in the Chapter 3. This shows evident consistency with the post-seismic building configuration, providing a reliable correspondence between the attained model and the actual building. Consequently, this also benefits the ensuing tasks as the model reliably represents the real structure.

This Chapter presented a characterization of the case-study building adopted for the validation of the methodology. It was demonstrated how the attained model reliably reflects the effective building disrupted configuration, enabling the following research tasks to adopt it for the validation of the research methodology.

## 5.4. Application of artificial intelligent techniques to structural analysis and optimization

The methodology proposed in this section represents the central part of Chapter 5. A series of scenarios are defined based on past seismic hazards lessons learnt and the subsequent damage to buildings, as presented in Chapter 2. As not all of them are suitable for progression throughout all three research stages, an initial overview of which ones pertain to the different stages is provided. Following to that, the 3 research stages are individually addressed with a specific characterization of each scenario.

This section shows how traditional approaches to structural analyses in face of seismic hazards can be enhanced by deploying intelligent ensembles in combination or in replacement of simulation software, with the benefit of relieving the designer from repetitive tasks. The majority of the proposed work is conducted in MATLAB, except from stage 1 which relies upon the Autodesk Robot API as also explained in Chapter 3.

### 5.4.1. Scenarios definition

Grounding on the literature review and the targeted identification of the most common failures in masonry-infilled RC structures, a list of scenarios has been defined in order to validate the proposed research approach. Table 5.3 namely lists the different scenarios and the applicability through the three research stages. Each of the identified scenarios entails the investigation and optimization of a set of variables which were deemed as relevant for the seismic performance of the building, both based on the formerly conducted literature review and the evidence-based nature of this research.

At the same time, each scenario has been further investigated through the characterization of different sub-scenarios as shown in Table 5.4. The scenarios and the sub-scenarios differ in the techniques adopted for the optimization process, the EDP employed and the level of automation. For ease of identification, bespoke IDs have also been devised as presented in Table 5.4. Namely, the first part identifies the scenario based on the classification provided in Table 5.3. The acronyms SO and MO refer instead to the single or multi-objective nature of the optimization which is benchmarked through the adoption of different variables. Where IDR is specified is the scenario ID the inter-storey drift ratio is adopted as a benchmark EDP, otherwise it is implicitly adopted node displacement. Ultimately, the acronyms PL and AL stand for the potential user interaction.

**Table 5.3:** Scenarios identification and applicability through research stages.

| | ID | Scenario description | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|---|---|
| 1 | S1 | Frame members sections (including reinforcement) | 🟧 | 🟧 | 🟧 |
| 2 | S2 | Concrete class | 🟧 | | |
| 3 | S3 | Masonry infills (struts) | 🟧 | | |
| 4 | S4 | Permanent non-structural loads on slabs | 🟧 | | |

As formerly alluded to in the Methodology Chapter, object properties in the API are characterized by the definition of labels. However, in order to perform optimization tasks, it is necessary to collect the labels and to this respect two strategies were devised. The first one entails user interaction through the definition of a selected set of labels that the user is attempting to manipulate (i.e., PL, provided labels). Conversely, the automated scenario (i.e., AL) allows to detect all the labels existing in the model for a specific object (e.g., label sections regarding beam elements) without user intervention and optimize them. With respect to this scenario, the number of investigated variables is unknown a priori and it is conditional on the amount of labels included in the project.

**Table 5.4:** Characterization of research scenarios.

| | Scenario ID | Optimization strategy | | EDP | | User interaction | | Investigated variables |
|---|---|---|---|---|---|---|---|---|
| | | Single | Multi | Node displacement | IDR | Yes | No | |
| S1 | S1_SO_PL | x | | x | | x | | 2 |
| | S1_MO_1P_PL | | x | x | | x | | 2 |
| | S1_MO_1P_AL | | x | x | | | x | variable |
| | S1_MO_IDR_PL | | x | | x | x | | 2 |
| S2 | S2_SO_PL | x | | x | | x | | 1 |
| | S2_MO_1P_PL | | x | x | | x | | 1 |
| S3 | S3_SO_PL | x | | x | | x | | 2 |
| | S3_MO_1P_PL | | x | x | | x | | 2 |
| S4 | S4_SO_PL | x | | x | | x | | 7 |
| | S4_MO_1P_PL | | x | x | | x | | 7 |

It is pertinent to mention that in the context of single-objective optimization, the EDP considered as an objective consists in a single value represented by the aggregation of the three spatial components (i.e., x, y and z). Conversely, for multi-objective optimizations the value of the selected EDP for each spatial direction represents an individual objective. Therefore, where the Scenario ID includes the acronym 1P it is referred to the IDR or node displacement considered in a specific building node and represented by its 3 directional components separately, constituting the 3 objectives.

For scenarios S2-S4 the node displacement has been kept as a benchmark for stage 1 as it has been noticed that it provides better results than the IDR in that research stage. However, when progressing the analysis throughout the all three stages the IDR is a better choice. Detailed information regarding each scenario are provided in the sections to follow according to their pertinence for the specific research stage.

### 5.4.2. Stage 1: Investigation on building features

As formerly alluded to in the methodology description, the building investigation stage is often hindered by the impossibility of fetching all the information needed for the characterization of a structure preventing the adoption of a traditional approach. Therefore, the combination of 3D laser scanning data and computational techniques can help overcoming this issue advantaging the time schedule. The designated investigated features for each scenario are known from 3D laser scanning or site investigation when geometrical, or through numerical characterization relatively to mechanical properties. However, in order to validate the methodology proposed herein, the designated variables for each scenario are assumed as unknown.

Stage 1 entails adopting a GA technique to find the most likely value for the scenario-specific variables object of investigation. The API is invoked at each iteration of the algorithm in MATLAB in order to perform structural behaviour simulations and consequently fetch and benchmark the object variables.

Given the impossibility of physically measuring the structural displacements, the benchmark values adopted for the optimization were collected thanks to the digital representation of the building based on the 3D-laser scanning campaign and numerically verified through structural simulation analysis based on the displacement time series from the 2008 Wenchuan earthquake.

$$IDR = [2.07\%\ ;\ 0.86\%\ ;\ 0.11\%] \quad \text{(a)} \qquad disp = [-52\ ;\ -67\ ;\ -1.67] \quad \text{(b)}$$

**Equation 5.11:** Benchmark values for IDR (a) and node displacement (b).

Namely, the benchmark arrays for the IDR and node displacement calculated in the junction between the two blocks with different elevation are presented in Equations 5.11 and contextualized in the building in Figure 5.11. The values for both the EDPs are in the order of the x, y and z-oriented components and while the IDR is represented in percentage, the node displacement is herein provided in millimetres.

**Figure 5.11:** Detail of the column analysed as a singularity element given its location in the junction between the building blocks presenting different elevations.

A pertinent consideration that applies to all the scenarios is related to the time of the simulation as it is acknowledged to be a critical aspect. In order to avert overloading the hard drive with temporary file hindering the performance and increasing optimization times, two strategies are adopted. In cases where the design variables can be subjected to high variability, such as for structural elements section, the labels from the previous iteration are deleted and new ones are created. Alternatively, in cases where the range of variability is less significant, such as for the concrete class, a flag to identify a pre-existing labels with the same properties is created. If the label is not found, hence it is not in the model, a new one is created featuring the properties determined by the GA.

#### *5.4.2.1. Scenario 1*

Scenario 1 features the geometric features pertaining the RC frame and Table 5.5 presents the constraints adopted in the context of the genetic algorithm definition. As it can be observed by the table, the scenarios suitable for the applicability of these constraints and GA settings are all the ones pertaining to the S1 group, except for the automated one. The objective for optimization consists in the minimization of the discrepancy between the effective EDP value $EDP_{REAL}$ and the one attained at each GA iteration $EDP_{GA}$.

As formerly alluded to, the number of variables for the automated (i.e., -AL) scenario varies according to the labels included in the model, therefore the constraints definition is customised at each iteration based on a bespoke algorithm.

**Table 5.5:** Scenario 1 characterization.

| **Scenario Features** | **Description** |
|---|---|
| Name | S1_SO_PL, S1_MO_1P_PL, S1_MO_1P_AL |
| Description | The size of main frame elements (i.e., beams and columns) is investigated without operating on the material features |
| Number of variables | 4 (SO_PL), 4 (MO_PL), variable (MO_AL), |
| Design variables | Beams and columns' height (i.e., BH, CH) and width (i.e., BB, CB) |
| Constraints | Assumption of square columns' section given field investigation (CB=CH).<br>BH> 1.2 CB<br>$30 \leq BH \leq 80$ cm<br>$30 \leq CB \leq 50$ cm<br>CB, BH $\in \mathbb{N}$ |
| Variables following to constraints application | 2: CB (=CH), BH |
| Research question applicability | RQ1,RQ2,RQ3 |
| **GA settings** | |
| Objective | Minimum discrepancy between calculated displacement and real value |
| Number of generations (GA) | 30 |
| Population number | 80 |
| Average simulation time | 45 s |
| Average optimum number of generations | 10-15 |
| Stopping criteria | Displacement discrepancy in x,y and z directions < 0.001 cm |

Assuming square columns' sections (CB=CH) in this case study given the evidence-based constrains and also being the columns' side equal to beams' section base (CB=CH=BB), the only variables left to investigate are CB and BH. Consequently, the array V containing the input values for each iteration of the GA is showed in Equation 5.12 in its generic formulation, however for the proposed case study $n$=2 and $m$=3 would be considered.

$$V = [CB_1 \; CB_2 \dots \; CB_n \; BH_1 \; BH_2 \dots \; BH_m]$$

**Equation 5.12:** GA input variables array structure

Furthermore and preliminary to the constraints definition, it has to be taken into account that linear inequality constrains are expressed in MATLAB in the form of Equation 5.13 [295], where A represents the coefficient matrix. Therefore, each constraint condition represents an inequality and the ensemble of them has to be formulated in a matrix form. In order to overcome the case-specificity of the constraint definition, Equation 5.14 shows how the different coefficients $R_k$ were calculated based on the model values of the investigated variables in order to establish a proportional relationship across the dimension of the elements. The final matrix containing the inequalities, hence constraints relationships, is then formulated in Equation 5.15. It has to be highlighted that this is functional to establish a cap for the variation of geometrical features, however the values of the individual variables are allowed to range according to their pre-defined lower and upper bounds.

$$\boldsymbol{A} \cdot x \leq \boldsymbol{b}$$

**Equation 5.13:** Linear inequality constraints structure in MATLAB

$$\frac{CB_i}{CB_1} \leq R_k \;, \qquad \frac{BH_j}{CB_1} \leq R_k \qquad i{=}2, \ldots n\;; j{=}1 \ldots m;\; k{=}1 \ldots (i+j-1)$$

**Equation 5.14:** Constraint definition for the investigated variables. $CB_i$ , $CH_i$ = column's sides, $BB_i$ , $BH_i$ = beam's width and height

$$\begin{bmatrix} -R_1 & 1 & 0 & \ldots & 0 \\ -R_2 & 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ldots & 0 \\ -R_k & 0 & 0 & \ldots & 1 \end{bmatrix} x \leq \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

**Equation 5.15:** Constraint definition for the investigated variables

With respect to the reinforcement, the structural behaviour software does not allow to input it in the model as it is considered just an output of the calculation. In order to overcome this problem, the reinforcement is only investigated in the third stage.

#### *5.4.2.2. Scenario 2*

The second scenario aims at fetching the most likely concrete class $R_{ck}$ adopted for the frame. As it can be observed from Table 5.6 the GA in this case does not elaborate a value for the design variable, but it adopts the position of the element in the array containing the different options for the concrete compressive resistance.

**Table 5.6:** Scenario 2 characterization.

| **Scenario Features** | **Description** |
|---|---|
| ID | S2_SO_PL, S2_MO_1P_PL |
| Description | The concrete class is investigated |
| Number of variables | 1 |
| Design variables | Rck |
| Constraints | Rck_options = [25 30 35 40 45 50 60]<br>option = index identifying the element in the Rck_options array<br>option ∈ ℕ, option ∈ [1,7] |
| Variables following to constraints application | 1 (option) |
| Research question applicability | RQ1 |
| GA settings | |
| Objective | Minimize $\lvert EDP_{GA} - EDP_{REAL} \rvert$ |
| Number of generations (GA) | 30 |
| Population number | 80 |
| Average simulation time | 35 s |
| Average optimum number of generations | 10-15 |
| Stopping criteria | $\lvert EDP_{GA} - EDP_{REAL} \rvert$< 0.001 cm |

The index, labelled as “option” in Table 5.6, can vary between 1 and 7 as the allowed concrete classes are 7 in total and their values are fetched by the Chinese regulatory framework. The average time per simulation is here shorter than it was for the frame as there is just one label to be modified for each GA iteration.

### *5.4.2.3. Scenario 3*

The current scenario explores the optimization of infill walls in order to evaluate the most likely option for the as-built condition. As previously explained in the context of masonry infills characterization, when adopting the model proposed by Stafford-Smith [223] for infill stiffness and Mainstone’s one for the struts’ section height [292], just two variables are needed for the characterization.

**Table 5.7:** Scenario 3 characterization.

| **Scenario Features** | **Description** |
|---|---|
| ID | S3_SO_PL, S3_MO_1P_PL |
| Description | The concrete class is investigated |
| Number of variables | 1 |
| Design variables | Masonry characteristic compressive resistance ($f_k$) and infill thickness (tt) |
| Constraints | tt ∈ ℕ, tt ∈ [20, 40] (cm)<br>$f_k$ =∈ ℝ, $f_k$ ∈ [1, 10] (N/mm$^2$) |
| Variables following to constraints application | 2 ($f_k$ , tt) |
| Research question applicability | RQ1 |
| **GA settings** | |
| Objective | Minimize $\lvert EDP_{GA} - EDP_{REAL} \rvert$ |
| Number of generations (GA) | 30 |
| Population number | 80 |
| Average simulation time | 50 s |
| Average optimum number of generations | 10-12 |
| Stopping criteria | $\lvert EDP_{GA} - EDP_{REAL} \rvert$< 0.001 cm |

As shown in Table 5.7, only the characteristic compressive resistance of masonry $f_k$ and the infill thickness *tt* need to be tweaked in the context of the GA. Given the evidence-based nature of the research, the boundaries for masonry infill thickness are based on field investigation and cross reference with the point cloud data-based model.

### *5.4.2.4. Scenario 4*

This section addresses the investigation on permanent non-structural loads applied on internal floors and the slab composition. The castellated slab is not included in the investigation as its features are known based on the on-site characterization formerly outlined in this Chapter. As shown in Table 5.8, this scenario contains the highest amount of variables which is acknowledged to represent a critical aspect and potential affect the precision. The flooring strata have been identified based on the composition sketched in section 5.3.3 while the constraints for load values reflect the GB 50009-2001.

**Table 5.8:** Scenario 4 characterization.

| **Scenario Features** | **Description** |
|---|---|
| ID | S4_SO_PL, S4_MO_1P_PL |
| Description | Permanent non-structural (PNS) loads investigation and slab composition |
| Number of variables | 7 |
| Design variables | (1) Screed thickness, (2) concrete specific weight, (3) indoor flooring, (4) partition walls load, (5) ceiling load (e.g., counter ceiling), (6) plaster density and (7) outdoor flooring |
| Constraints | LB,UB (1) = [0.05 , 0.08] (m)<br>LB,UB (2) = [4 , 24] (KN/m$^3$)<br>LB,UB (3) = [0.02 , 1.5] (KN/m$^2$)<br>LB,UB (4) = [0.27 , 0.54] (KN/m$^2$)<br>LB,UB (5) = [0.1 , 0.55] (KN/m$^2$)<br>LB,UB (6) = [5 , 19] (KN/m$^3$)<br>LB,UB (7) = [0.65 , 3.3] (KN/m$^2$) |
| Variables following to constraints application | 7 |
| Research question applicability | RQ1 |
| **GA settings** | |
| Objective | Minimize $\lvert EDP_{GA} - EDP_{REAL} \rvert$ |
| Number of generations (GA) | 30 |
| Population number | 80 |
| Average simulation time | 40 s |
| Average optimum number of generations | 10-12 |
| Stopping criteria | $\lvert EDP_{GA} - EDP_{REAL} \rvert$< 0.001 cm |

### 5.4.3. Stage 2: Data-reduction process and neural network design

This section analyses the second stage of the research as presented in Figure 5.12, which can be further separated into (i) an initial sensitivity analysis and the ensuing data-reduction process conducted with PCA and (ii) the strategy adopted to define the ANNs architecture. The following two subsections will then address accordingly the two steps identified in Figure 5.12.

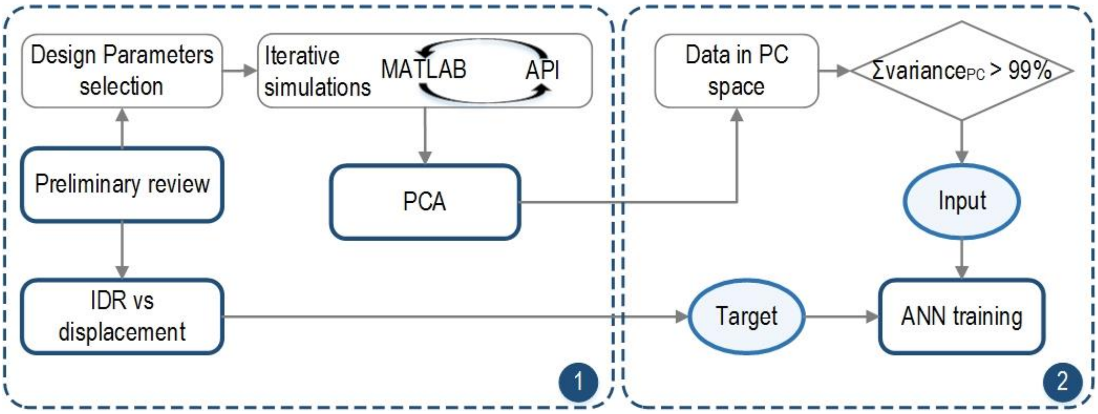


**Figure 5.12:** Stage 2 structure.

### *5.4.3.1. Sensitivity analysis and Principal Component Analysis*

This section addresses the data-reduction process which serves a twofold purpose: (i) identifying the governing variables for the building performance and (ii) reducing the data set that will be adopted for the ANN training. The sensitivity analysis entails the iterative alteration of specific variables (i.e., building features or properties) in order to ensure a reliable variability to the data set that will be then adopted for the neural training. This is attained by iteratively invoking the Robot via COM-based API in MATLAB and performing structural behaviour analyses [213].

For the scope of this research 1000 simulations were conducted and at the end of each a set of outputs are collected in a matrix as well as the design variables. The structure of this matrix, as well as the design variables and the output are presented in Table 5.9 where both the generic and case-specific number of elements for each variables are specified. The outputs adopted for this step consist in both the selected EDPs (i.e., IDR and node displacement) and reinforcement data. The reinforcement-related outputs are functional to eventually train a specific ANN for this purpose, as it will be presented in stage 3.

**Table 5.9:** Sensitivity analysis matrix structure.

| | **Design variables** | **Number of elements** | |
|---|---|---|---|
| | | **Generic** | **Case study** |
| | Columns' sections dimensions | Variable | 6 |
| | Beams' sections dimensions | Variable | 4 |
| | Concrete characteristic compressive resistance ($R_{ck}$) | 1 | 1 |
| | Permanent structural loads (slabs) | Variable | 2 |
| | Permanent non-structural loads (slabs) | Variable | 3 |
| | Masonry infills loads | 1 | 1 |
| | Snow load | 1 | 1 |
| | Masonry characteristic compressive resistance ($f_k$) | 1 | 1 |
| | Thickness of masonry infills | 1 | 1 |
| | **Results** | **Number of elements** | |
| | | **Generic** | **Case study** |
| | Node displacement | 3 | 3 |
| Selected target for Design ANN | IDR | Storey number - 1 | 3 |
| Target for Reinforcement ANN | Stirrups density ($mm^2/m$) | 3 | 3 |
| | Longitudinal reinforcement percentage | 3 | 3 |
| | Node displacement (1 node) | 3 | 3 |

A relevant observation regarding this research stage pertains the criterion according to which the variables are tweaked. The variability is established according to Table 5.11 and it is conditional on the remainder of the ratio between 10 and the last figure of the iteration number. Considering that the remainder of the division always falls in the interval between 0 and 9, five different combinations are established as shown in table 5.10.

**Table 5.10:** Sensitivity analysis variability matrix for scenario 1.

| Remainder | | Columns section | Beams section | Loads | Infill loads | Snow | Concrete class | Infills thickness | Masonry $f_k$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 6 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ | ✗ |
| 2 | 7 | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| 3 | 8 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✗ | ✗ |
| 4 | 9 | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ |
| 5 | 0 | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ | ✗ | ✗ |

In this phase, while extrapolating the reinforcement data, it will always be considered the most stressed element as in the initial situation in order to ensure coherency of the data. Therefore, in the as-built situation the most stressed element in the storey registering the highest IDR is collected. Over the ensuing simulations that structural element is referred so that the ANN is trained with uniform data. Besides, Table 5.9 also highlights that the two ANN engines are trained with separate sets of data according to the output expected from them.

The second step entailed in this research stage consists in the application of the PCA algorithm. The relevant outputs are the variance and coefficient matrixes. The initial data matrix is then multiplied by the coefficient one in order to attain the data in the PC space. However, the number of PCs to be considered is determined by the total variance represented by the cumulative sum of each PC’s variance. The number of PCs representing at least 99% of the total data set consists in the final PC number that is going to be adopted as input for the ANN training. On the other side, the target for the training of the ANN is adopted in one case as IDR and in the other in terms of displacement. The latter indicators have been used as objectives in the first stage of the research (i.e., investigation of unknown parameters) while in this context they consist in the target for the ANN training. Another relevant output of PCA consists in the coefficient matrix that enables the transformation of the initial variables into the PC space at each iteration of the ANN.

#### *5.4.3.2. Neural network architecture*

This section presents the rationale behind the neural network architecture development, although detailed results will be introduced in §5.5.2. The determination of the neural network architecture is pursued through a trial and error approach where increasing complexity (i.e., hidden layers) is introduced while adjusting the neurons in a way such to avert overfitting. Therefore, when increasing the number of hidden layers, the number of neurons for each layer is decreased or adjusted based on the outputs of the previous simulation to maximise the overall performance. To do so, the discrepancy between training and test phases has to be observed as its entity is a flag for potential overfitting. A total of 11 experiments were conducted adopting an increasingly higher abstraction for the network.

The adopted network is eventually constituted by 4 hidden layers and 14 neurons in total, where 5 are allocated for each of the first two hidden layers and 2 for the last two. The network is then trained with *Bayesian Regularization* algorithm given its applicability with potentially noisy datasets. The transfer function adopted for information exchange amongst the neurons is a *log-sigmoid* as it is mostly employed for multilayer neural networks.

### 5.4.4. Stage 3: Optimization and forecasting

This research stage aims at showcasing the strategy adopted to replace the structural simulation engine with an intelligent ensemble, benefitting both the quality of the results and time. Furthermore, the applicability of this strategy stretches from design (i.e., new constructions) to post-disaster assessment (i.e., existing buildings), but also including damage forecasting when using performance-based approaches. The benefits for resilience are evident given the risk-based nature of this approach and the potential for exploration and integration of mitigation strategies complying with building regulations.

In light of the above, the methodology featuring this stage is totally disentangled from the integration with the API as the latter is replaced by the ANN engine trained during the second step of stage 2, as presented in the former section. Figure 5.13 shows explicitly how the integration between the GA and the ANN is attained, clarifying how the latter therefore replaces the structural simulation software.

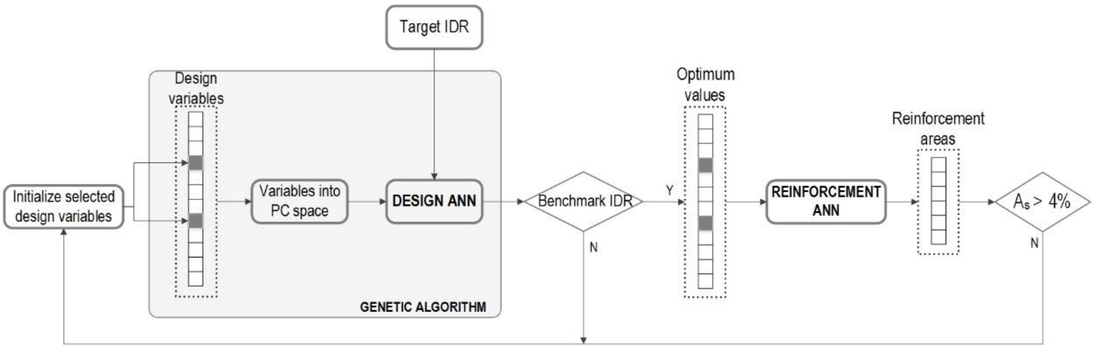


**Figure 5.13:** Stage 3 substructure with combination of Design and Reinforcement ANNs.

The GA operates tweaking specific variables in the input array of the Design ANN and eventually benchmarking its Output with the Real value. If the discrepancy does not exceed the Benchmark, the optimization can be stopped and the optimum values are therefore attained. Subsequently, the optimum design variables represent the input for the Reinforcement ANN which then generates reinforcement areas. The final check is on the maximum longitudinal reinforcement area, which is taken from Eurocode 2 [296] corresponding to a cap of 4%.

Namely, the proposed methodology requires to define only the benchmark EDP value, as per building regulation. Therefore, to effectively correlate the building damage to regulatory frameworks, the damage scale proposed in Table 5.11 is adopted as a result of the review presented in Chapter 2. Concerning the Eurocodes and considering (i) the different IDR limitations according to the ductility of non-structural elements attached to the structure and (ii) the building's state-of-the-art prior to the hazard; a cap of 0.5% is taken. This stems from the considerable amount of cladding adopted in façade in terms of ceramic tiles that negatively perform in dynamic conditions, increasing the weight of the structure and their non-ductile nature.

**Table 5.11:** Damage scale addressing earthquake disruption level to RC structures. S: structure, O: openings, I: infills.

| Damage Index | FEMA 356 | SEAOC Vision 2000 | Eurocode 8 | Calvi (1999) |
|---|---|---|---|---|
| D0 | - | - | | - |
| D1 | Immediate occupancy IDR ≤ 1% or negligible, transient or permanent | IDR < 0.2% transient<br>Permanent negligible | IDR ≤ 0.5% | Damage ≤ LS1<br>IDR ≤ 0.1% |
| D2 | | IDR< 0.5% transient<br>Permanent negligible | | LS1 < Damage ≤ LS2<br>0.1% < IDR ≤ 0.3% |
| D3 | Life safety<br>IDR ≤ 2% transient<br>IDR ≤ 1% permanent | IDR< 1.5% transient<br>IDR< 0.5% permanent | Chord rotations | LS2 < Damage ≤ LS3<br>0.3% < IDR ≤ 0.5% |
| D4 | Near collapse<br>IDR < 4% transient or permanent | IDR< 2.5% transient or permanent | | LS3 < Damage ≤ LS4<br>0.5% < IDR ≤ 1.5% |
| D5 | | IDR > 2.5% transient or permanent | | Damage > LS4<br>IDR > 1.5% |

In order to further investigate the building features, also reinforcement is addressed and specifically this is attained through the following steps:

- Identification of the storey with the highest IDR;
- Within the storey, selection of the most stressed beam (i.e., $B_n$) and column (i.e., $C_n$) based on the maximum value between shear and moment achieved for a specific load combination (i.e., $L_c$), as in Equation 5.16. With respect to beams, the maximum moment and shear is picked between the middle span and supports given the inversion of the diagram in those positions;

$$\text{(a)} \quad C_n = C(\max(S(L_C), M_y(L_C)) \qquad \text{(b)} \quad B_n = B(\max(S(L_C), M_y(L_C))$$

**Equation 5.16:** Selected column I (a) and beam (B) (a) based on maximum value between shear (S) and bending moment ($M_y$) attained for the different load combinations ($L_c$).

- Additionally to those elements, further singularity elements (i.e., corner column as to Figure 5.11) are also included in the calculation in order to account for geometric irregularities of the building's frame;
- The reinforcement is then calculated in 5 points for the previously selected elements and specifically to the most demanding load combination along the beam/column.
- The maximum value for both shear and moment reinforcement is then picked amongst the minimum required values, as outlined in Equation 5.17. Longitudinal reinforcement is represented in percentage while stirrups are calculated in mm$^2$/m of beam's length.

(a) $$A_{col,R} = \max(\min\left(A_{s,R}(C_n)\right))$$ (b) $$A_{beam,R} = \max(\min\left(A_{s,R}(B_n)\right))$$

**Equation 5.17:** Selection criteria for reinforcement areas both in case of columns (a) and beams (a).

Stage 3 is also characterised by the generation of three different datasets featured by increasing variable number and complexity, as presented in Figure 5.14. The first dataset is conditional just on geometric variables (i.e., CB, CH, BB and BH) namely entailing the frame members sizes, while the second dataset involves the masonry-related variables also featuring the third scenario (i.e., masonry characteristic strength $f_k$ and infill thickness $tt$). Ultimately, the third dataset adds the consideration of loads to the previously described variables.

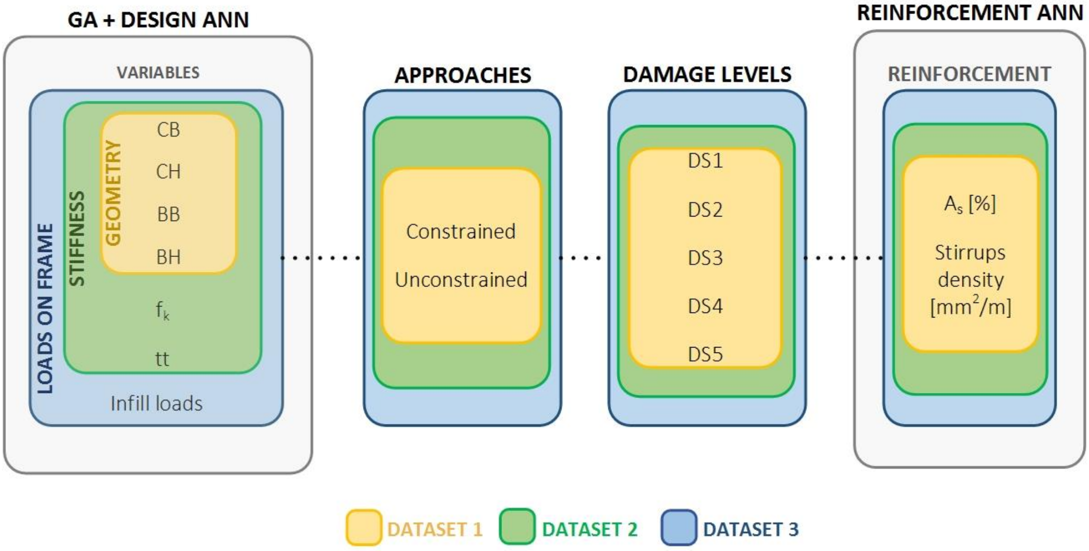


**Figure 5.14:** Variables and approaches entailed in the generation of each data set produced throughout stage 3.

In a concrete scenario, this provides the opportunity of changing the infill stiffness properties but adjusting the masonry material features (i.e., density) in a way such as not to vary the loads. Conversely, the third data sets would allow complete variability of both stiffness of the struts and hence the infills, but also including the adoption of different masonry typologies. Nonetheless, the above would not entail any modifications to the openings in façade.

The calculation of the infills load $W_i$ is performed at each iteration of the GA and ANN engines (i.e., Design and Reinforcement) according to the formulation provided in Equation 5.18b. Namely, the load of is obtained multiplying the ratio $R$ of infill thicknesses $tt$ for two subsequent iterations, assuming the masonry density constant. It is however acknowledged how this assumption might result in loss of accuracy while instead varying its characteristic compressive resistance $f_k$. In fact, different brick and masonry producers might provide materials which underwent different treatments and therefore are featured by slightly diverse physical properties. However, for the purpose of this research it is considered enough to adopt this approach while further improvements can be implemented in future work.

$$R = \frac{tt_{i-1}}{tt} \quad \text{(a)} \qquad\qquad W_i = R \cdot W_{i-1} \quad \text{(b)}$$

**Equation 5.18:** Calculation of masonry infill weights: tt= masonry infill thickness, W= weight of masonry infill.

Due to the preliminary on-site observations, a significant parameter to be taken into account in terms of results consisted in the inertia discrepancy between horizontal and vertical frame elements (i.e., beams and columns). Namely, considering the longitudinal axis as y, the inertia of each structural elements is calculated as in Equation 5.19. In order to adopt a generic approach, the columns' section is considered rectangular and therefore it is not possible to exactly forecast its orientation during the optimization process. Additionally, in order to account for the maximum dynamic inertia of the section in the occurrence of a seismic event, the maximum second area moment between the two directions was considered as outlined in Equation 5.19(a). Conversely, given the structural nature of the beams and given that stresses act mostly perpendicularly to their longitudinal axis, it is reasonable to calculate the inertia across the horizontal direction, as shown in Equation 5.19(a).

$$I_c = \max\left(\frac{CH \cdot CB^3}{12}, \frac{CB \cdot CH^3}{12}\right) \quad \text{(a)} \qquad I_{b,y} = \frac{BB \cdot BH^3}{12} \quad \text{(b)}$$

**Equation 5.19:** Calculation of section inertia for columns (a) and beams (b).

## 5.5. Results

This section provides the results pertaining the application of the methodology proposed in the current Chapter after its deployment on the case study building, Beichuan Hotel and adopting the 2008 Wenchuan earthquake in order to ensure a solid grounding. The first sub-section will address the results pertaining the investigation stage, referred as stage 1. Section 5.5.2 addresses instead the performance of the Design neural networks and the choice of the EDP. Ultimately, section 5.5.3 provides an extensive breakdown of the results attained adopting the combination of the Design and Reinforcement neural networks for damage prediction.

The presented results can be summarized as follows:

- Investigation of specific building features through the integration of commercial structural behaviour simulation tools and AI module;
- Calculation of optimum values for a specific set of variables which can foster a more risk-based seismic design of RC structures;
- Damage forecasting and assessment both at the building and district level thanks to extrapolation criteria based on key building features.

### 5.5.1. Investigation on building features using GA and API

The first stage of the research approach encompasses the investigation of certain set of variables assumed as unknown. Table 5.12 provides a breakdown of the scenarios and pertaining sub-scenarios with a specification of the EDP adopted for each of them. The precision level refers to the discrepancy between the attained results and the real values for each investigated variable.

**Table 5.12:** Results from stage 1 for different scenarios.

| Scenario ID | Benchmark (EDP) | Precision level |
|---|---|---|
| S1_SO_PL | Node displacement | 99.3% |
| S1_MO_1P_PL | Node displacement | 99.8% |
| S1_MO_1P_AL | Node displacement | 85.7% |
| S1_MO_IDR_PL | IDR | 96.9% |
| S2_SO_PL | Node displacement | 67% |
| S2_MO_1P_PL | Node displacement | 67% |
| S3_SO_PL | Node displacement | 84.6% |
| S3_MO_1P_PL | Node displacement | 79.9% |
| S4_SO_PL | Node displacement | 42.6% |
| S4_MO_1P_PL | Node displacement | 42.1% |

It is pertinent to mention that the precision is calculated as the mean value between the individual precision for each variable. Results for scenario 5 are not produced according to what has been explained in section 5.4.2.5 regarding the assumption of full building knowledge, hence the possibility of directly moving to stage 2.

Figures 5.19-5.21 show the numerical results for the pertaining investigated variables in the context of each scenario. The observation of Figures 5.15-5.17 and Table 5.13 evidences an evident inverse correlation between the number of variables and the level of precision attained. In particular, scenario 4 registered the lowest precision, despite some of the variables managed to be investigated with suitable accuracy (e.g., external flooring).

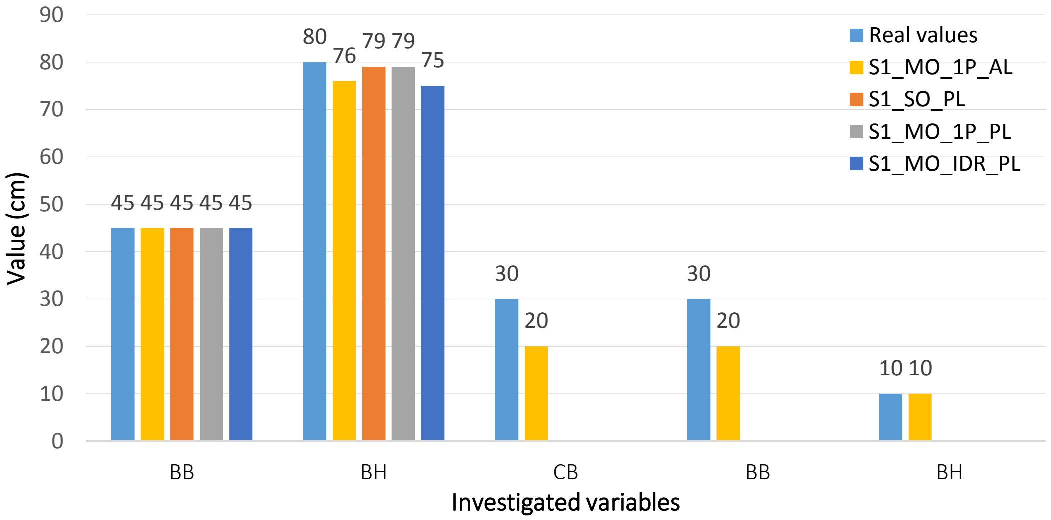
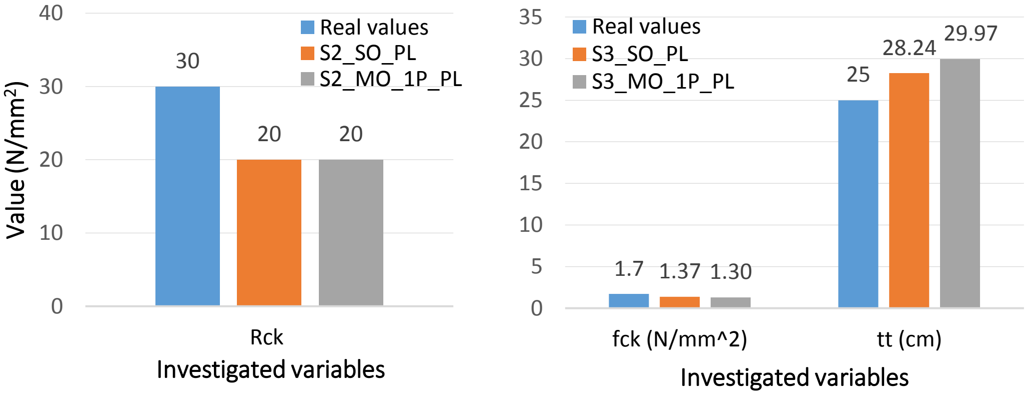


**Figure 5.15:** Comparison between values attained across the different investigation algorithms for Scenario 1. The acronyms for the investigated variables are the following: column section base (CB) and height (CH), beam section base (BB) and height (BH).



(a) (b)

**Figure 5.16:** Comparison between values attained across the different investigation algorithms for Scenario 2 (a) and 3 (b).

The choice of introducing multi-objective optimization was motivated by an expectation of higher accuracy given the possibility of individually targeting each displacement component. Nonetheless, this assumption did not prove to find effective confirmation in the results attained.

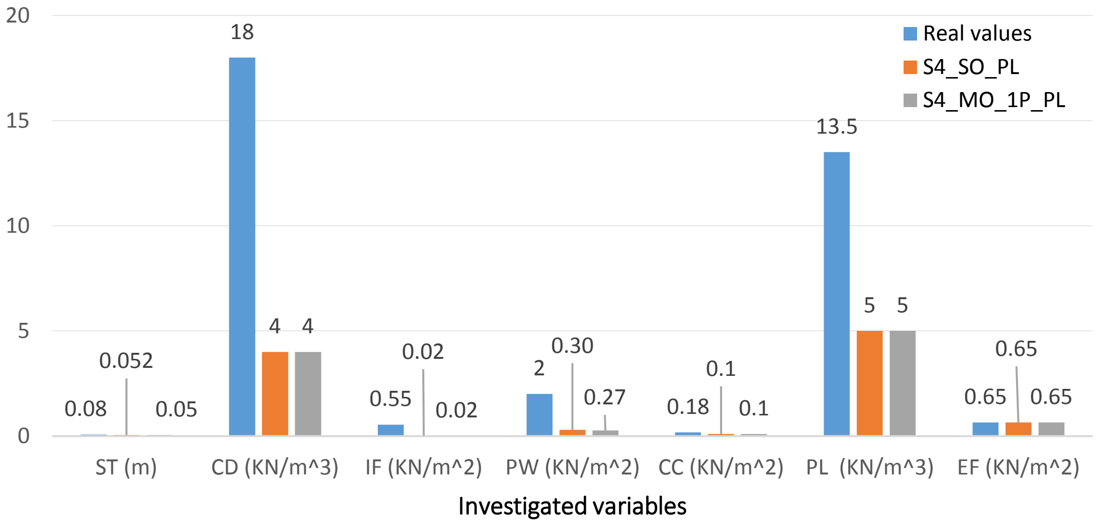


**Figure 5.17:** Comparison between values attained across the different investigation algorithms for Scenario 4. The investigated variables are represented by the following acronyms: Concrete screed thickness (ST), concrete screed density (CD), Internal flooring (IF), counter-ceilings (CC), plaster (PL), external flooring (EF).

### 5.5.2. Choice of EDP and neural network

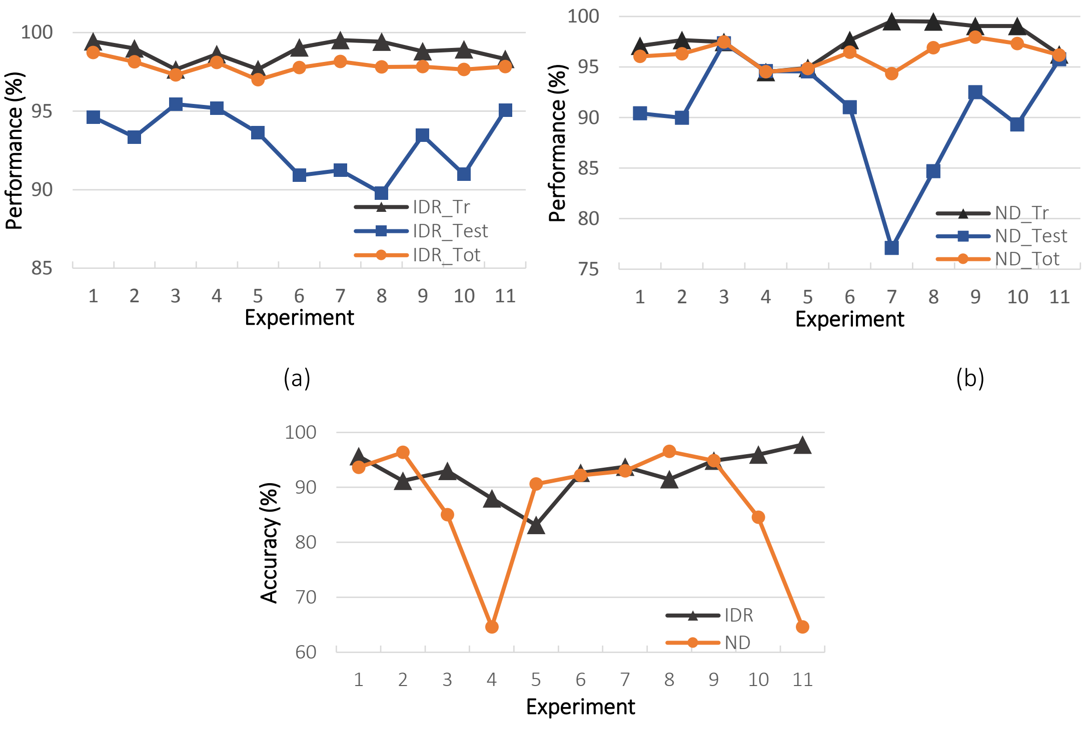
This section outlines the experiments conducted in the second research stage to establish the architecture of the neural network that will be employed in stage 3 and the choice of the EDP. Following to the PCA an average of 12 PCs appeared to be representative for the 99.6% of the initial dataset. As a result, the eigenvectors represent the input for the tested neural networks.

**Table 5.13:** Experiments to determine the optimum neural network architecture for the optimization phase (i.e., stage 3).

| | | | $R^2$ Training [%] | | $R^2$ Test [%] | | $R^2$ overall [%] | | Results accuracy [%] | |
|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | **Layers** | **Neurons, Layers { : }** | **IDR-ANN** | **ND-ANN** | **IDR-ANN** | **ND-ANN** | **IDR-ANN** | **ND-ANN** | **IDR-ANN** | **ND-ANN** |
| 1 | 1 | 20 | 99.44 | 97.08 | 94.62 | 90.42 | 98.72 | 96.04 | 96 | 94 |
| 2 | 2 | 10 | 98.99 | 97.65 | 93.36 | 89.98 | 98.13 | 96.31 | 91 | 96 |
| 3 | 2 | 2 | 97.65 | 97.48 | 95.44 | 97.36 | 97.31 | 97.47 | 93 | 85 |
| 4 | 2 | 8 | 98.63 | 94.51 | 95.18 | 94.6 | 98.1 | 94.52 | 88 | 65 |
| 5 | 3 | 3 | 97.67 | 94.9 | 93.62 | 94.56 | 96.99 | 94.85 | 83 | 91 |
| 6 | 3 | 8 | 99.06 | 97.65 | 90.91 | 91.03 | 97.76 | 96.47 | 93 | 92 |
| 7 | 3 | 10 | 99.52 | 99.54 | 91.23 | 77.09 | 98.16 | 94.34 | 94 | 93 |
| 8 | 4 | 8 | 99.42 | 99.5 | 89.77 | 84.69 | 97.8 | 96.91 | 92 | 97 |
| 9 | 4 | 6 | 98.8 | 99.04 | 93.46 | 92.5 | 97.82 | 97.95 | 95 | 95 |
| 10 | 4 | 20{1} , 1 {2÷4} | 98.93 | 99.04 | 90.96 | 89.32 | 97.65 | 97.31 | 96 | 85 |
| 11 | 4 | 5{1,2} , 2 {3,4} | 98.31 | 96.23 | 95.07 | 95.76 | 97.82 | 96.16 | 98 | 65 |
| | | | | | | | | **Mean accuracy** | **92.49** | **86.90** |

Two types of neural networks are trained and tested, adopting the EDPs analysed in Chapter 2 and discussed above, namely IDR and node displacement (ND). A trial-and-error process is adopted to devise the test ANNs, as presented in Table 5.13, entailing a total of 11 simulations starting with a single-layer neural network and progressing with an increasing complexity. Table 5.13 introduces to this regard the conducted experiments, the number of hidden layers considered for each neural network, the pertinent number of neurons and the attained results accuracy for both IDR and node displacement (ND) as targets.

The calibration of the proposed neural networks is done by calculating the same variables investigated over stage 1 for the scenario S1_SO_PL, namely frame sections features. As outlined by Figures 5.18a and b, the overall performance of IDR-trained neural network is more stable although the ND-ANN exhibits a better fit between training and test, specifically for experiments 3, 4 and 5 and 11. However, the highest accuracy is attained by the IDR-trained ANN for the experiment 11 as visible in Figure 5.19c and 5.18c, where the results precision is the highest of the whole dataset and corresponds to about 98%.



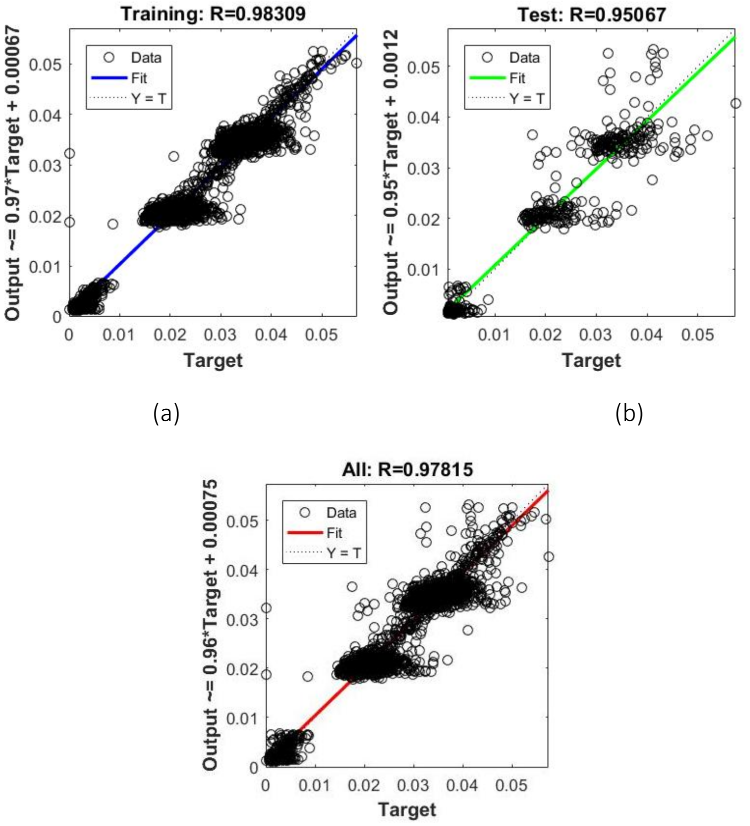
(a) (b)

(c)

**Figure 5.18:** Analyses on devised neural networks in terms overall performance for the different EDPs, IDR (a) and node displacement (ND) (b). The accuracy of results in then compared across the two ANNs (c).

The results evidence that the ND-trained neural network provides better results for single or double-layer neural networks, whereas the IDR neural network sustains a more consistent performance even varying the architecture. With respect to the IDR ANN and comparing

Grounding on the above observations, the IDR-trained ANN is chosen over the ND and specifically the 4-layer neural network devised for experiment 11. An additional advantage of the IDR over the ND as a target, is the potential for regulatory compliance, as evidenced in the literature review provided in Chapter 2.



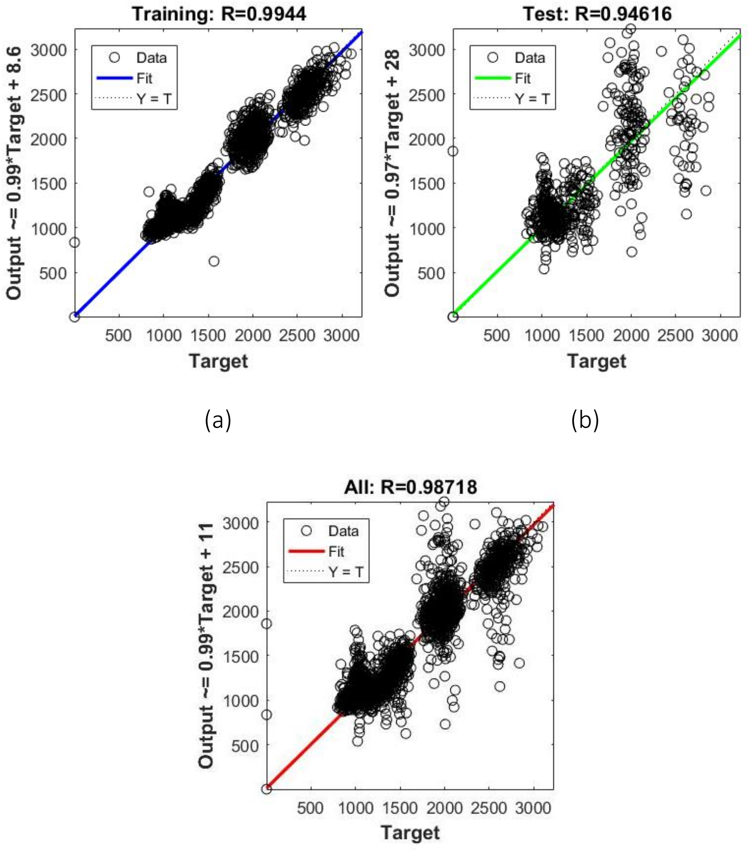
(a) (b)

(c)

**Figure 5.19:** Design ANN training features adopting IDR as target for experiment 11. Training (a), Test (b) and overall (c) performance features.

Figures 5.18a and c it is observed how the overall performance of the network is higher for a single layer network than it is for the 4-layer ANN of experiment 11. However, the latter is chosen upon the higher accuracy of the results provided when performing the variables calculations, which shows an improvement of 2% respect to the ANN of experiment 1.

Figure 5.19 shows the performance plots for the selected neural network, evidencing how an approximate 3% discrepancy is registered between training and test, exhibiting no signs of overfitting. Besides, the data are consistently clustered around the 45° degrees line evidencing a good fit for the data set. Figure 5.20 shows instead the Reinforcement ANN, which exhibits instead an overall performance of almost 99%, although registering a higher discrepancy between training and test of about 5%.



(a) (b)

(c)

**Figure 5.20:** Reinforcement ANN Training (a), Test (b) and overall (c) performance features.

### 5.5.3. As-built values vs neural network results

This section presents the validation of the proposed methodology with respect to scenario S1_SO_PL and addressing specifically stage 3. This is an evolution of stage 1, where the Robot API is replaced by the bespoke Design ANN adopting the IDR as a target.

Figure 5.21 represents instead a comprehensive overview in relation to the variables involved in all three datasets and the results attained by the selected ANN which draws on deep learning techniques. Overall, the accuracy attained is significantly high, except from the masonry resistance $f_k$ where a drop is exhibited.

As also described in former sections in relation to the sensitivity analysis procedure, the algorithm automatically detects the storey undergoing the highest IDR and inside this storey the most stressed structural elements are then picked for stress data collection. It was verified in this respect that, coherently with the real failure mechanism of the building, the storey showing the highest IDR was the first one.

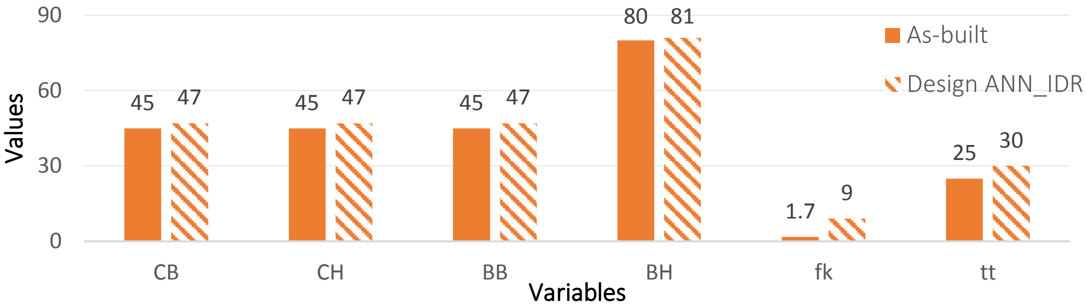


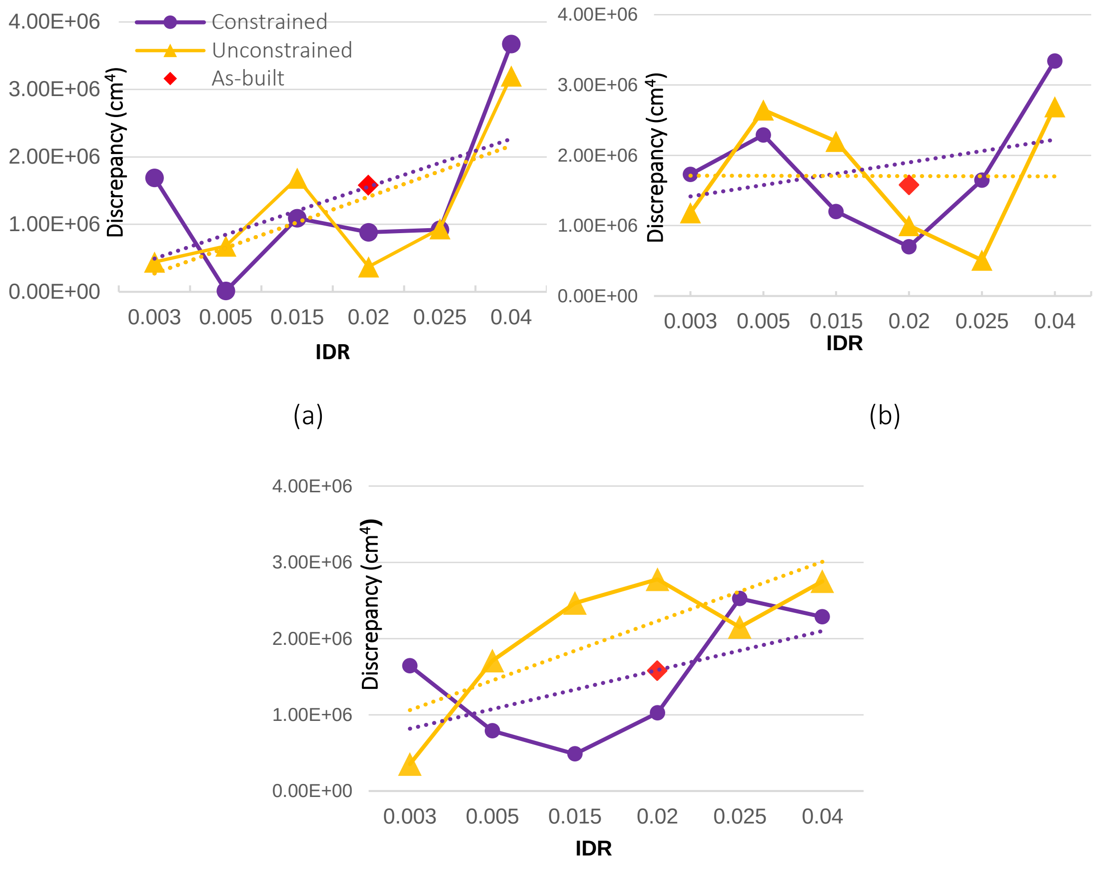
**Figure 5.21:** Comparisons between results attained through the ANN engine trained adopting the IDR as a target and the effective values. $f_k$: characteristic compressive resistance of masonry [N/ mm$^2$]; *tt*: masonry infill thickness [cm]; CB,CH,BB,BH: frame sections [cm].

In accordance with the current building configuration, the first storey shows the highest vulnerability given the drastic change of global rigidity in contrast with the ground floor. Given the above considerations it can be then confirmed the consistency between the results attained through this stage of the research and the as-built situation. As a consequence of the results provided herein, the choice of the EDP selected for both stage 1 and stage 3 falls on the IDR given its significantly higher accuracy in the prediction stage as a replacement of the simulation engine.

### 5.5.4. Calculation of optimum frame and reinforcement

This section aims at providing a breakdown of the results attained through the deployment of the third stage of methodology for the scenario S1. Even though S1 focusses mainly on the frame structural members over the investigation phase (i.e., stage 1), its holistic consideration of a wider set of variables throughout stage 3 is evidenced by the development of three different datasets, as formerly explained. The current research stage mainly focuses on the deployment of the GA-ANN ensemble for the purpose of damage prediction and risk forecasting. The Design ANN iteratively produces values for the designated variables which are consequently benchmarked by the GA adopting the inter-storey drift ratio as an indicator for the building performance. This is also enhanced by the adoption of a second neural network specifically devised to generate reinforcement areas for frame members, as extensively outlined in the methodology section.

As a result of the structural damage appraisal and visual assessment of the building during the field investigations it was observed that the disproportion between the inertia of columns and beams might have hindered the stability of the building under the seismic action. This represents a factor usually worth considering during the design stage of building located in earthquake-prone areas. To this regard, it is analysed in detail the discrepancy between horizontal (i.e., beams) and vertical (i.e., columns) structural elements. These results are plotted in Figure 5.22 and they respectively relate to each of the three datasets described previously.



(a) (b)

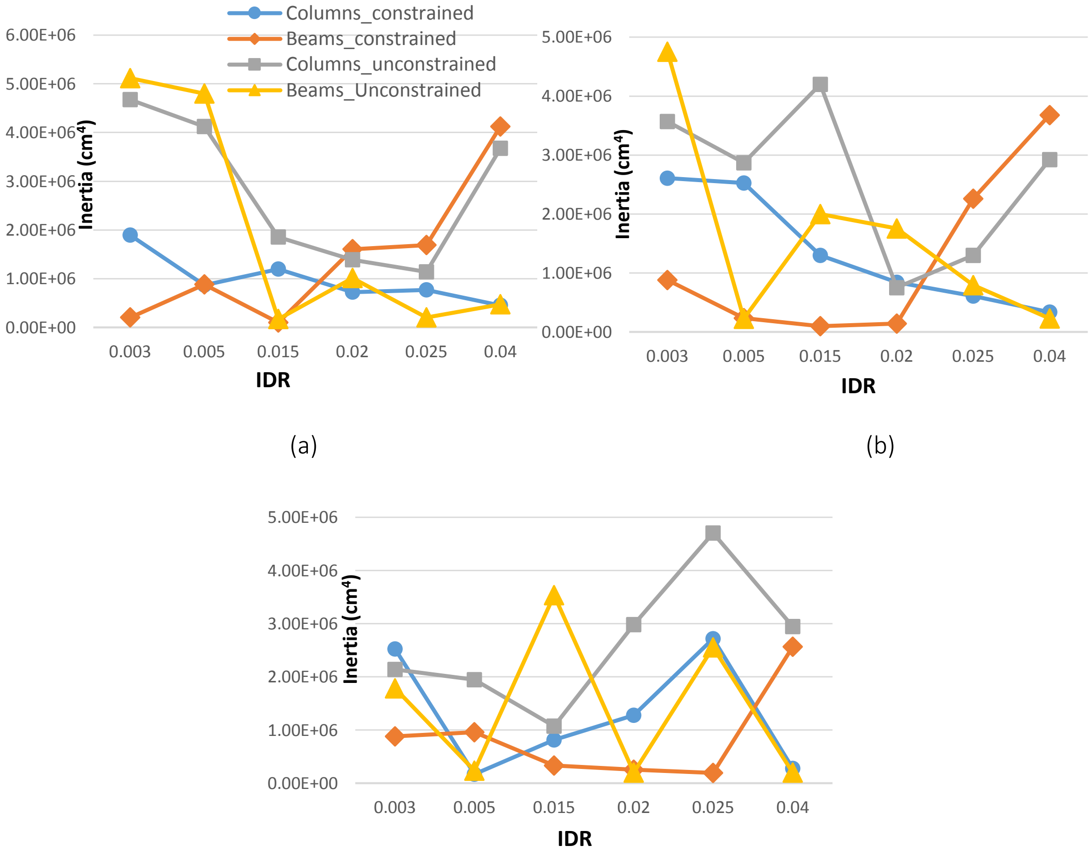
(c)

**Figure 5.22:** Inertia discrepancy of frame section elements (i.e., beams and columns) in relation to the first (a), second (b) and third (c) set of data.

The correlation amongst level of damage (i.e., IDR) and section inertia discrepancy is evidenced by the results plotted in Figure 5.22. Figures 5.22a and 5.22b display in fact a rather realistic performance scenarios where the highest level of damage coincides with the highest inertia discrepancy amongst structural elements. The third dataset, which results are visible in Figure 5.22c, shows however an anomaly in relation to the unconstrained condition, while the constrained values are consistent with what attained in the other simulations.

The as-built discrepancy is in fact lower for each optimized data set, except from the unconstrained condition in the context of the third data set. This apparent irregularity in the data can also be explained looking at the section inertia for columns and beams separately both in constrained and unconstrained conditions. Specifically Figure 5.22c shows that in correspondence to 2% the discrepancy between columns and beams is significant but still in favour of the columns.

With respect to frame members sizing, a damage level reduction (e.g., IDR equal to 0.5%) could have been attained enhancing columns' shear capacity as also displayed in Figure 5.22a. Comparing in fact the as-built condition with a hypothetical IDR of 0.5%, it is evident how a better reinforcement design in face of shear actions would have benefitted the sections. This is endorsed by the results provided in Figure 5.24a, which show that a reduced damage level could have been attained increasing the ductility of columns by the provision of a higher percentage of longitudinal reinforcement. The reinforcement needed to attain an IDR corresponding to 4% appears however higher than the one necessary to achieve an IDR of 0.5%, which is likely due to the unbalanced proportion of reinforcement/concrete area.

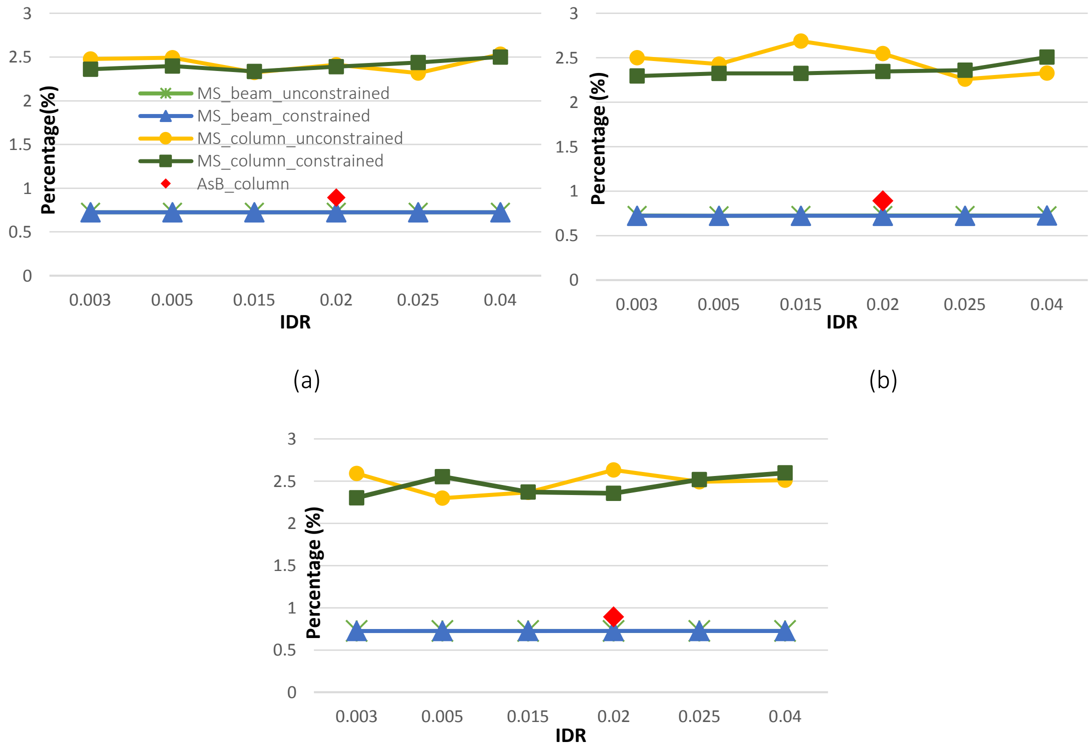


(a) (b)

(c)

**Figure 5.23:** Inertia section values for individual variables (i.e., beams and columns) in relation to the first (a), second (b) and third (c) set of data.

Figures 5.24-5.27 show the comparison between the reinforcement percentages in the corner column in as-built (i.e., AsB) conditions and the calculated values through the algorithm in terms of minimum reinforcement areas. Given the impossibility of fetching reinforcement information for beams, only columns data are displayed in the diagrams in relation to the as-built configuration.



(a)

(b)

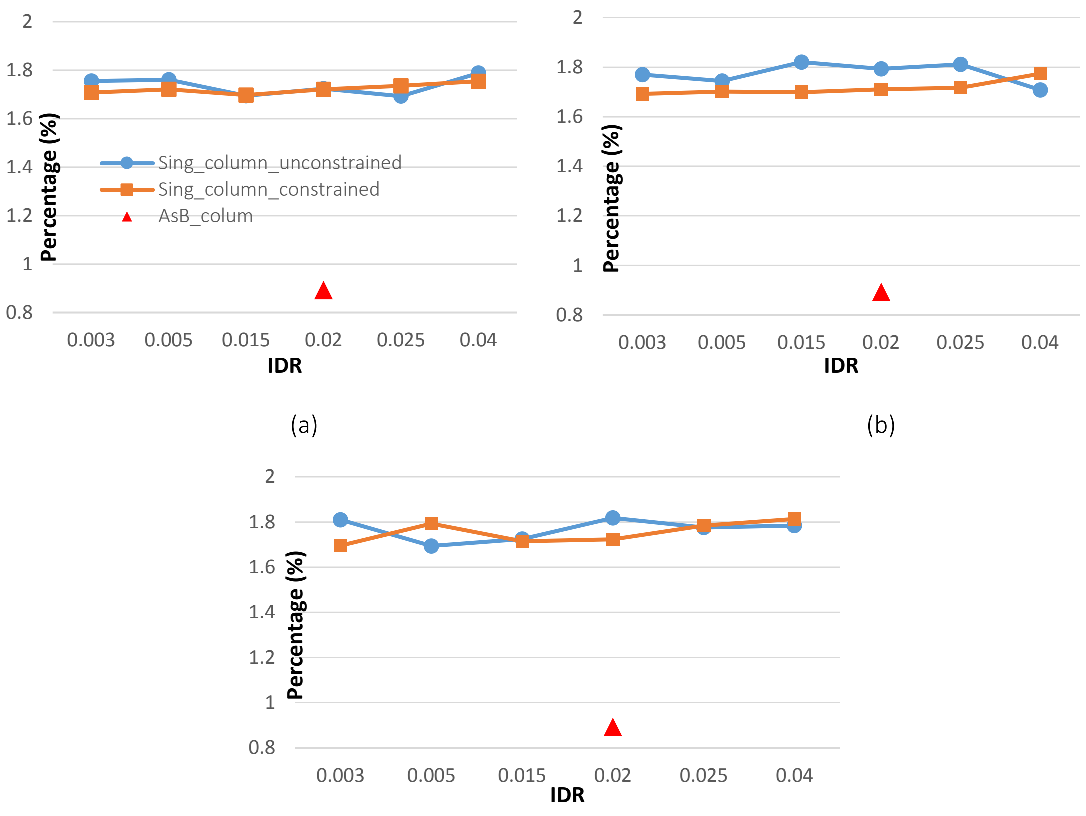
(c)

**Figure 5.24:** Longitudinal reinforcement percentage of most stressed beam and column for the storey registering the highest IDR, respectively relatively to the first (a), second (b) and third (c) data sets.

A comparison between Figures 5.24 and 5.25 reveals that despite the most stressed elements require more reinforcement in terms of area, the column located in the corner is subjected to more fluctuations. The plotted data demonstrate the need for a tailored design of both longitudinal and transversal reinforcement conditional on the expected performance.

Overall, longitudinal reinforcement areas for columns appears to exceed the one required for beams. This is also consistent with the occurrence of seismic events where the horizontal acceleration component exceeds the vertical one. This assumption is further endorsed by the required stirrups density required for columns over beams, as shown in Figure 5.26.

For coherency with former research stages, the GA-ANN ensemble was in this phase also adopted to investigate in detail section sizing of relevant frame structural members. The resulting values are compared with the as-built (i.e., AsB) configuration for a target IDR of 2% and consisting in the effective damage level undergone by the building.



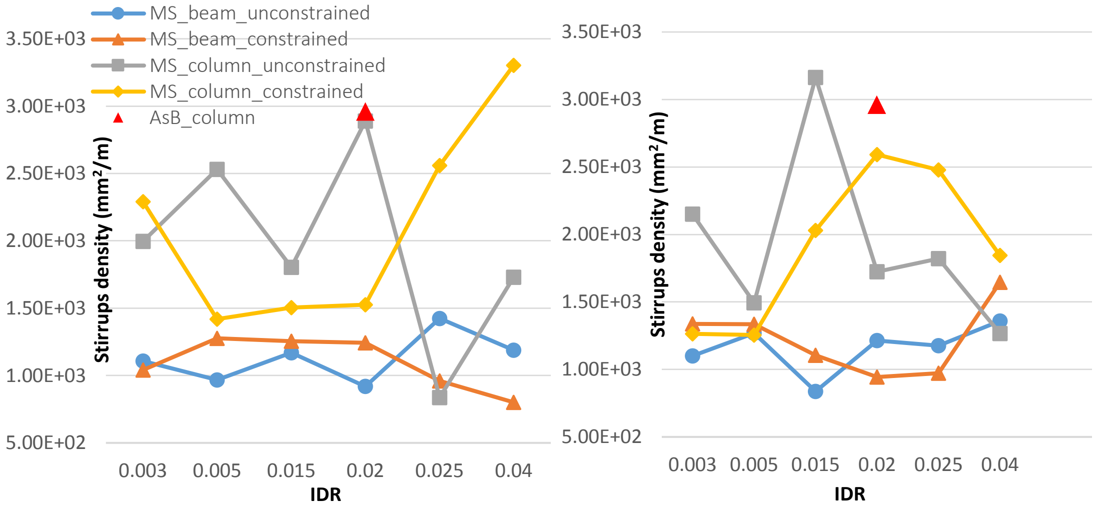
(a)

(b)

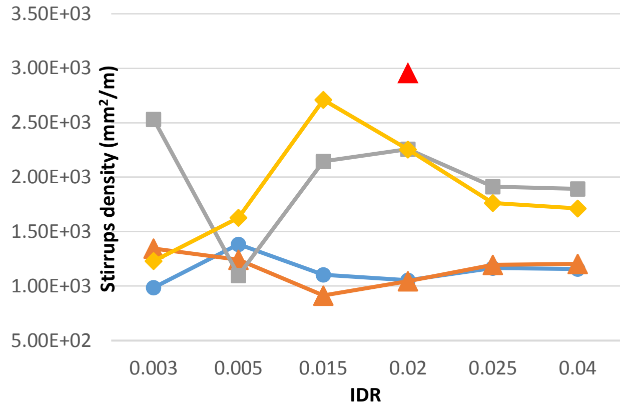
(c)

**Figure 5.25:** Longitudinal reinforcement percentage of corner column for the storey registering the highest IDR, respectively relatively to the first (a), second (b) and third (c) data sets.

This analysis is also carried out in relation to the constrained scenario where the column's cross-section is square and its side (i.e., CB=CH) equals the beam's section base (i.e., BB). The motivation behind these constraints can be found in the definition of Scenario 1, which is also evidence-based hence reflecting the as-built geometry. Based on the results analysed so far, the second dataset appears to provide the best improvements in terms of optimization in relation to the as-built configuration.

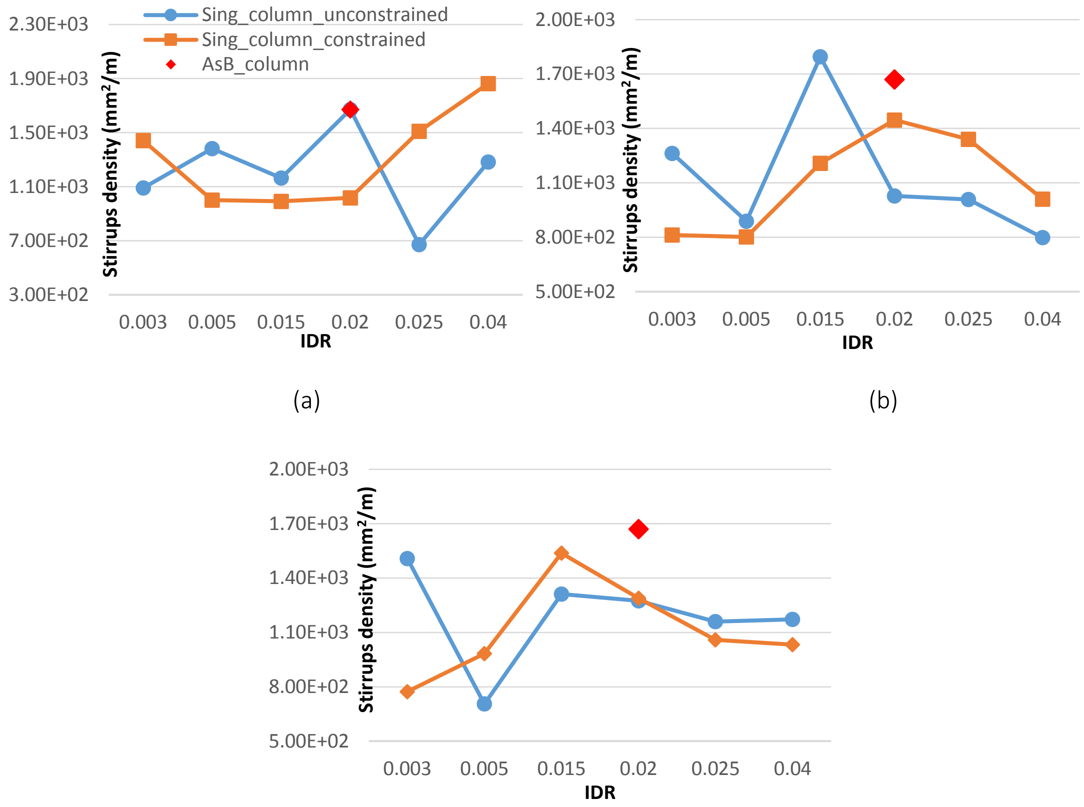


(a) (b)



(c)

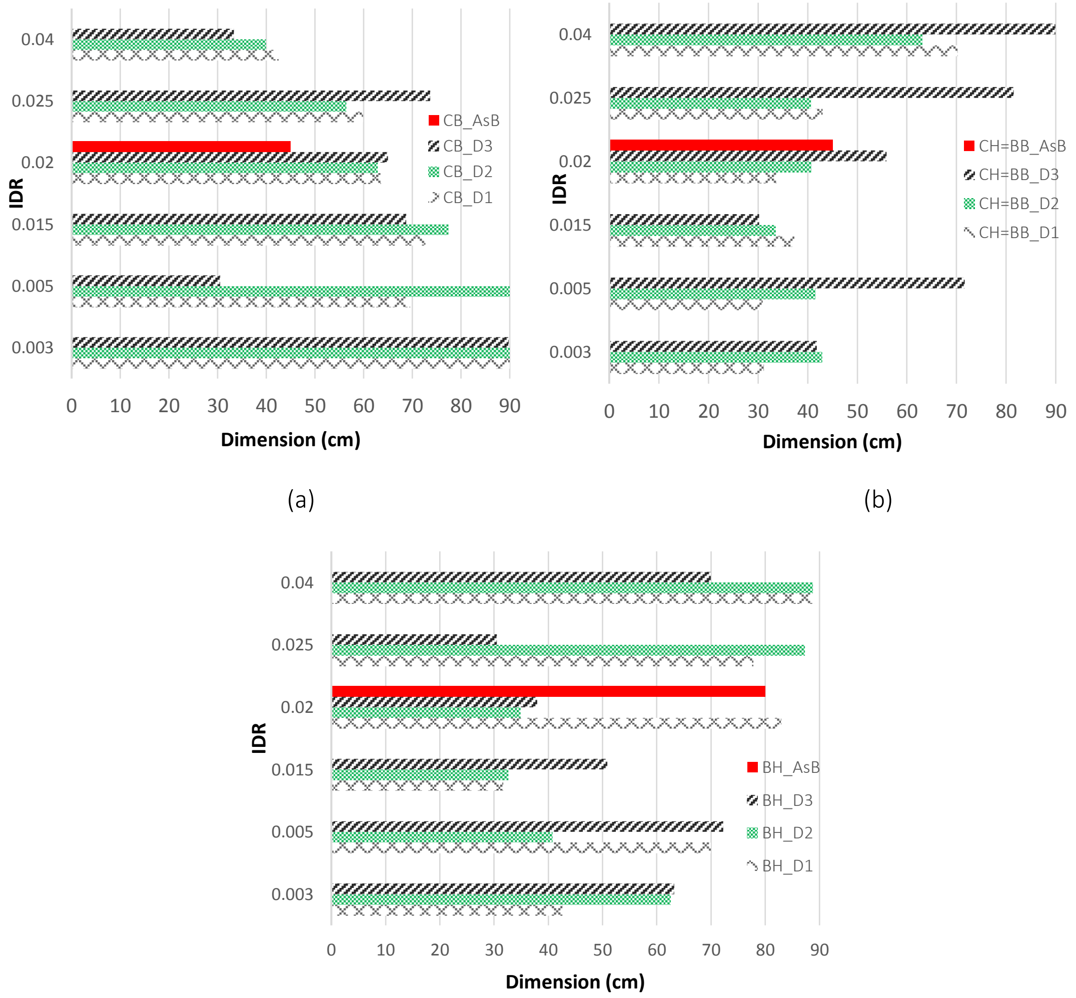
**Figure 5.26:** Stirrups density of most stressed column and beam for the storey registering the highest IDR, respectively relatively to the first (a), second (b) and third (c) data sets. MS=most stressed.



(a) (b)

(c)

**Figure 5.27:** Stirrups density corner column and beam for the storey registering the highest IDR, respectively relatively to the first (a), second (b) and third (c) data sets.



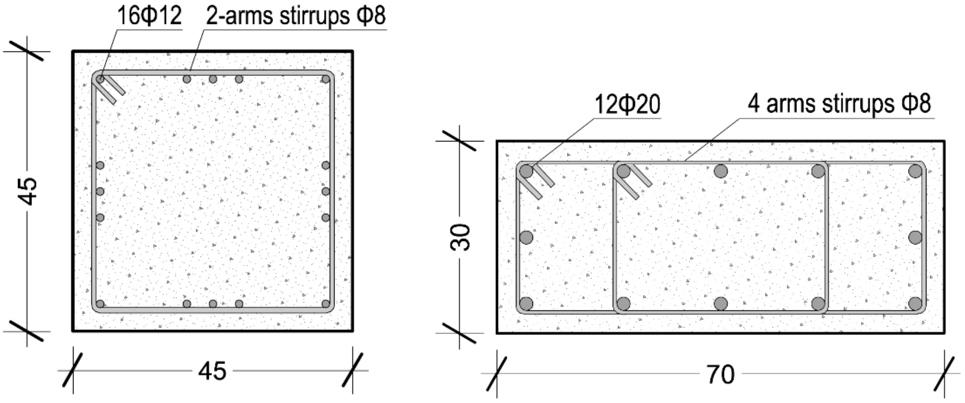
(a) (b)

(c)

**Figure 5.28:** Comparison between as-built (AsB) condition and different frame section sizing across the three data sets in constrained conditions for CB (a), CH=BB (b) and BH (c).

In light of the presented results it is possible to devise solution that could have been adopted to enhance the structural performance of the building in face of the hazard. Figures 5.29a and 5.29b respectively present the cross-sections of the corner columns in its as-built condition and in its optimized design. The latter results for the adoption of the results provided by the utilization of Dataset 1 with a target IDR of 0.5% and a longitudinal reinforcement area of 1.72%. Through the introduction of 12 φ20 bars an overall percentage of longitudinal reinforcement corresponding to 1.76% was achieved satisfying the minimum required area.

With respect to shear reinforcement, the proposed methodology allows to narrow down the calculation to the level of mm$^2$ of stirrups per each meter of length of structural member. As a result, knowing the required reinforcement shear area and considering the shape of the column's section, a 4-arms configuration for the stirrups is preferred to ensure a suitable level of binding amongst the bars. Additionally, a diameter φ8 is adopted with a spacing of 15 cm between the stirrups along the columns. In contrast with the optimised solution, the as-built cross-section as displayed in Figure 5.29a exhibits a significant lack of longitudinal reinforcement combined to an incorrect distribution of the reinforcement.



(a) (b)

**Figure 5.29:** Comparison between current column section for a 2% IDR (a) the calculated one for a 0.5% of IDR (b).

With respect to the as-built section, it is worth noting that the Chinese seismic code GB 50010-2001 adopted for the case study building prescribes a minimum of 0.2% longitudinal reinforcement for each columns' side. Additionally, according to the aforementioned regulation, and specifically referring to corner columns, the requested minimum area in case of the lowest seismic intensity is 0.8%. Referring to the section in Figure 5.29a and excluding the overlapping bars in the corner, the column's side with the lowest longitudinal reinforcement area shows 4φ12. This approximately corresponds to percentage of 0.22% while the total of 16φ12 in the whole section corresponds to 0.89%. Both of the above described conditions are therefore satisfied in terms of longitudinal reinforcement area. The choice of considering the lowest seismic grade in this consideration is motivated by the impossibility of knowing in retrospect which seismic accelerations were considered for design.

In relation to shear reinforcement, the GB 50010-2001 also contains specific requirements for hoops. Considering a hoop diameter φ6, the most likely spacing according to the Chinese regulatory framework corresponds to either 6 or 8 times the diameter of the hoop, as it appears lower than 10-15 cm following to site investigations. As a result and given the above considerations, the sections were effectively designed in accordance to in-effect building regulations.

## 5.6. Discussion

Following to the results presented in previous sections it is evidenced how an optimization-based approach augmented with deep learning techniques can concretely benefit structural design, investigation and resilience enhancement strategies. Results evidence that building features can effectively be investigated with a reliable level of accuracy by benchmarking the structure's performance with EDPs (i.e., node displacement and IDR).

Preliminary considerations can be made in relation to the rather low precision level attained over the investigation phase (i.e., stage 1) specifically in relation to scenarios 2 and 4, whereas scenarios 1 and 3 registered a better performance. An approximate accuracy of 42% was attained for the load investigations, which might be mainly due to the consistent number of variables involved in this scenario, namely 7. Analogously, the second scenario registered an accuracy in terms of attained investigation concrete class of 67%. As opposed to scenario 4, the second one entailed the investigation of only one variable, therefore the scarce precision is likely to be motivated by different factors. A first hypothesis is related to the not determining role of the concrete class for the performance of this specific building, which would justify why varying its value the performance would not undergo significant changes. Another reason, from a wider perspective, could be the lower importance of the concrete class in relation to other factors [153].

It should be noted that the IDR initially was outperformed by the node displacement in the investigation phase. The multi-objective scenario adopting the IDR as a benchmark EDP (i.e., S1_MO_IDR_PL) registered in fact approximately 3% less accuracy compared to the scenario where node displacement was employed. Nonetheless, the IDR was eventually chose to be adopted across the three research stages as its performance and potential for regulatory compliance greatly outperformed the node displacement.

In terms of the results of the third research stage (i.e., stage 3) and considering the effective damage undergone by Beichuan Hotel represented by an IDR of 2%, it is evident that the building in its initial design was significantly under-dimensioned in relation to some of its features (e.g., reinforcement areas). This is particularly evident from Figures 5.24 and 5.25 specifically regarding longitudinal reinforcement. This statement is further endorsed by the cross-section represented in Figure 5.25a where a reinforcement deficiency is also evident. Conversely, the stirrups density appears to be comparable to the calculated minimum required values, as showed in Figure 5.26 and 5.27.

Nonetheless, a comparison between the section sizing pursued in Figure 5.25 and the inertial features of the frame members presented in Figure 5.22 reveals that more cost-effective solutions in terms of design could have been employed. It is worth mentioning that the section sizes plotted in Figure 5.32 are calculated on the basis of an expected IDR of 2%, in order to be comparable with the actual configuration of the building. However, such an IDR is not desirable hence it can be acknowledged that in order to pursue a significantly lower level of damage (i.e., IDR imposed of 0.5%) it is necessary to adopt a bespoke design that factors in the dynamic capacity of the structure. The data set that best fits the frame sizing individually is the first one and specifically the constrained option is selected, given its consistency with the real frame geometry in relation to the equality between the beam's section base and one column's side.

As a result, and for an expected IDR of 0.5%, it is possible to calculate the optimum inertial properties for each structural member typology as shown in Figure 5.28. Complimentarily, Figure 5.22 shows how the second area moment discrepancy for an IDR of 0.5% is significantly lower than the one registered for 2%. This is highly relevant as it shows the consistency with the hypothesis of a direct relationship between the damage undergone in the form of IDR and second area moment discrepancy between vertical (i.e., columns) and horizontal (i.e., beams) frame elements. Furthermore, an increase in structural resilience is ensured where the second area moment is higher for columns than it is for beams, albeit this appears more evident in the case of the constrained scenario as in Figure 5.23.

As formerly outlined, the combination of the GA, Design and Reinforcement neural networks enables the calculation of reinforcement areas for structural members. This is showed in Figure 5.26b where the optimised corner column cross-section is presented with the calculated reinforcement areas according to Figure 5.25a. Comparing the as-built cross-section with the optimized one and hypothesising a beam section equivalent to the one currently in place (i.e., section corresponding to 45 cm of base and 80 of height), it is evident the benefit in terms of inertia as the two sections. However, it is also pertinent to observe that the seismic action has to be considered in all the three spatial direction, therefore rectangular columns generally present a preferential failure plane, coinciding with the direction orthogonal to the prevailing section's side. To this regard it is relevant to highlight the importance of introducing shear walls in the design. It would be therefore of particular prominence from a practical design standpoint to combine to integrate the proposed methodology with an investigation for the optimum location of shear-walls.

The resulting second area moment discrepancy and the section sizing show how the structure's dynamic behaviour would have benefitted from the adoption of the proposed approach because of mainly two factors: (i) the simultaneous compliance to building regulations and (ii) the selection of the optimum option across a much wider set of options compared to the ones that could be considered through manual calculations. In terms of cost it is however worth observing that lower damage levels generally coincide with the need for more financial allowance. This is evident when designing according to modern building codes, characterized by strict requirements and penalizing coefficients for singularities in the structures and therefore often leading to over-dimensioned designs in the attempt of ensuring stability. Figure 5.28 evidences that more cost-effective solutions for frame structural members can be attained, preserving masonry infills properties. Cost is here considered increasing in correspondence of the increment of sections, assuming the two directly correlated.

However, Figure 5.28 also reveals the need for significant columns' sections dimensions even in coincidence with a high IDR, where the structure would instead be expected to be leaner and more deformable. This can be perhaps motivated by the significant shear action endured by columns during a seismic event. Specifically regarding the first dataset it can observed how the variability of sections despite the increase in IDR is not as significant as it could be expected. However, this can be explained by the preservation of the original masonry infill features, which are not included in the first data set, therefore inducing the frame to compensate in order to attain resilience enhancement. The observation of the three data sets displays how the inclusion of masonry infills in the optimization process benefits more columns' design rather than beams, which confirms the above considerations.

Nonetheless, it would be inaccurate to consider the frame alone neglecting the contribution of masonry infills, given their proven role in contributing to the overall structural rigidity [217, 227]. Therefore, in order to adopt a realistic approach, the third data set consists in the most representative as it provides a comprehensive consideration of the building properties. In light of the above and based on the results, it becomes evident the contribution to structural stability ensured by factoring the infills in the optimization process, which consequently leads to the adoption of leaner sections for the frame elements. As a result, this favours a more efficient and cost-effective construction material allocation simultaneously benefitting structural resilience.

The section sizing provided in Figure 5.28 is also key to disclose the potential for financial benefits related to the design and its factorization in the optimization process. Considering the current IDR represented by a 2% value and comparing it with the sections resulting from the second data set, it is evident how an optimization-based technique would have allowed to reduce of about 20% the volume of concrete adopted for construction. Similarly, referring to Figure 5.28 and assuming a target IDR of 0.5% for the second data set, the main increment in materials and consequently in costs would derive from columns. Figures 5.25b and 5.25c display how a reduction of IDR from 2% to 0.5% results into the beams' section and one of columns' sides to remain unchanged. Consequently, and according that what shown in Figure 5.28a, the main variability in terms of geometry would derive from the other columns' section side, reflecting proportionally on costs. These data show consistency with the above considerations about the columns accounting for the majority of seismic resistance. Therefore, an approximate 20% of additional cost could result in a reduction to up to a fourth of the damage.

On a different note, a comparison between Figures 5.26 and 5.27 reveals that both the singularity corner column and the most stressed elements featuring the storey with the highest IDR exhibit significant shear stress. Nonetheless, the fluctuation of the required stirrups density across columns is much more consistent than it is for beams, and particularly in relation to the column located in the corner position.

This leads to two main observations, the first one being the consistency with a seismically-stressed RC frame where columns are supposed to be mostly stressed in terms of shear rather than bending given the generally higher horizontal components of the seismic acceleration in relation to the vertical one. The second observation refers to the coherency between the aforementioned results and the initial hypothesis of the structural layout irregularity, inducing critical stresses in the portions of the building where a significant change in rigidity is registered. This is specifically the case of the height variation between the two blocks as in Figure 5, which leads to a local surge in the shear action of the analysed corner column and globally to torsional mechanisms triggering then the soft-storey phenomenon.

In addition to the above, the proposed ANN are evidently building-specific and their training has to be performed every time that a different building is analysed. Nonetheless, in case of pre-disaster conditions it is possible to create a taxonomy of different building typologies when scaling up the methodology at the district-level, so that the same ANN could be applied to different buildings. This clearly is allowed on condition that, within the typology, the buildings exhibit the same structural features in terms of sizing, layout and loading.

On the other hand, in post-disaster conditions the performance reduction of the building has to be taken into account and this differs from building to building. In this specific case, the ANN becomes exclusively building-specific.

Besides, when applying the same ANN to different buildings it is implicit the final level of precision attained will coincide, given that the structural systems have been deemed as equivalent a priori. On the other side, further calibration may be required when a different ANN has to be trained when a different structure has to be assessed. However, the apparent disadvantage in terms of time is recovered over the optimization phase.

## 5.7. Conclusion

This Chapter primarily addressed research questions 2 to 4 through the proposed three research stages, as follows:

- Stage 1 answered research question 2: *How can structural design parameters be inferred to accurately characterise and model a seismically compromised building in case of limited access to data and lack of supporting documentation?*
- Stage 2 addressed research question 3: *Can the governing variables most sensitive to the structural integrity of a building be inferred taking into account a wide range of considerations, including local environmental and geotechnical conditions?*
- Stage 3 tackled research question 4: *Can these sensitive variables inform the development of less computationally demanding structural analysis models with a view to optimize the structural design of a building?*

The proposed analytical methodology for resilience assessment and enhancement proved to outperform traditional approaches based on the evident benefits in terms of investigation purposes and optimization potential. Results evidence how an initial structural investigation process aided by evolutionary algorithms (i.e., GA) can supply the information lacking from traditional approaches hence bridging potential obstacles to data collection (e.g., impossibility to conduct direct measurements or unavailability of documentation). Further steps with an increasing computational complexity (i.e., stages 2 and 3) further expand the range of applicability of this approach. The replacement of the simulation software with an ensemble of evolutionary algorithms and neural networks able to optimize and provide both design variables and reinforcement areas drastically reduce the simulation time from several hours to few minutes benefitting also accuracy. It can be therefore concluded that deep learning techniques can effectively lead to resilience enhancement also benefitting financial target but mostly fostering human life safeguard.

In light of the above, it is therefore possible to highlight how the three research questions have been answered and a methodology to perform investigation (i.e., research question 2) and damage forecasting and optimization (i.e., research question 4). In addition, research question 3 was successfully answered by the adoption of sensitivity analysis, which allowed to select by means of the principal components identified by PCA, the most relevant variables to be adopted for the ANN training.

Overall, the proposed methodology allows to factor in the following aspects:

- Design scenarios entailing new buildings, disrupted structures or refurbishment interventions;
- Investigation of individual (i.e., single-objective optimization) or aggregated (i.e., multi-objective optimization) building features;
- Compliance with building regulations;
- All possible seismic analyses types;
- Pre and post-earthquake risk assessment for humans and buildings;
- Cost evaluation for interventions on existing structures or seismic-related losses.

All things considered, this technique stands out given its comprehensive approach in tackling structural analysis, as opposed to traditional techniques seldom involving all the above aspects simultaneously. Additionally, its transferability and potential for integration with any architectural or structural behaviour simulation tool makes it advantageous for practical applications. Given the adoption of deep learning and optimization techniques such as genetic algorithm and neural network ensembles, high-accuracy damage and risk forecasting are viable, making this methodology scalable both at the building at district level for a more cost-effective and leaner resilience-enhancement planning.

# 6. Integrating building and district-level resilience assessment for urban-scale damage forecasting

This Chapter aims at linking the micro and macro-scale approaches, respectively addressing resilience at the building and district level. Chapters 4 and 5 have respectively addressed the district and building-level approaches, while herein the objective is to organically combine them together showcasing the potential for their integration at the macro-scale. A comprehensive consideration of resilience in relation to the built environment in face of geo-environmental hazards has to factor in multidimensional variables being mutually influencing. This involves both the physical side (e.g., buildings and infrastructures) and the socio-organizational one (e.g., government, stakeholders and designers). This is also enriched by the adoption of a multidimensional mapping and applied to the Old Beichuan County, for consistency with the previous work. This work was initially published by Cerè et al. [214] and it has been adapted and further elaborated for the purpose of this research.

It is pertinent to observe that no research question is specifically addressed herein, however the aim of this Chapter is to provide a meaningful exemplification of how the qualitative and quantitative approaches can be coupled from an organizational standpoint. In addition, the current Chapter is also functional to outline the implications of this framework in the context a regulatory and policy-based perspective. This entails investigating how the integration of the proposed research would benefit different figures (e.g., policy-makers, private building owners) playing a relevant role towards resilience achievement.

## 6.1. Proposed approach

This section pertains the integration of district and building-level approaches starting from an overall outline of the methodology and proceeding with the characterization of the case-study. This is attained through a multi-dimensional mapping of the area and the development of a damage assessment scale combining the qualitative and quantitative perspectives. This analysis is conducted on Old Beichuan district, in the Wenchuan province, China.

### 6.1.1. Overview

As shown in Figure 6.1 the methodology proposed in Chapter 5 can be iterated on a series of buildings in order to cover a district-scale area. This would allow to attain a district-level damage prediction in face of a specific hazardous events. In Figure 6.1 it is also shown how the twofold potential for application of either the district-level approach alone (i.e., as-built condition) or its adoption in combination to the optimization strategy proposed in Chapter 5 (i.e., optimized). Namely, the latter would benefit new constructions but also post-disaster assessments. However, the most prominent contribution for the combination of the two approaches is represented by the opportunity of performing risk and damage forecasting.

In terms of resilience, $R_0$ would represent the resilience of the buildings and infrastructures' as-built condition whereas $R_{opt}$ stands for the resilience of the enhanced system. The difference between the two would provide the effective resilience enhancement, as demonstrated in Figure 6.1. It has to be pointed out that this Chapter applies to the damage level assessment and comparison between the as-built and optimized conditions. The whole resilience calculation is considered as future work as it would be subsequent to the Analytical Hierarchy Process (AHP) to be conducted on the data pertaining the district-level framework.

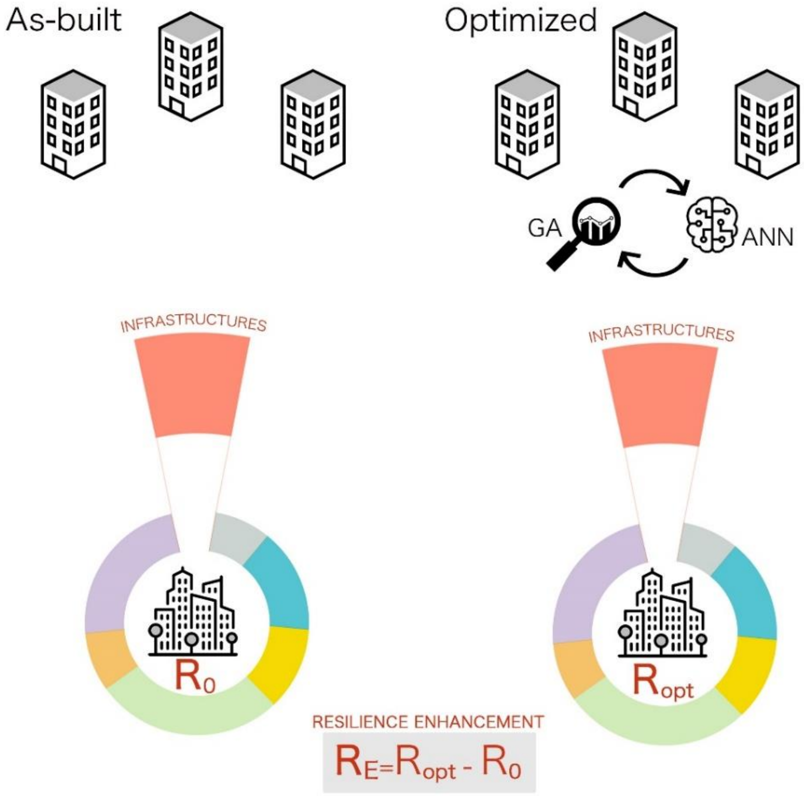


**Figure 6.1:** Proposed methodology for integration of building and district-level approaches.

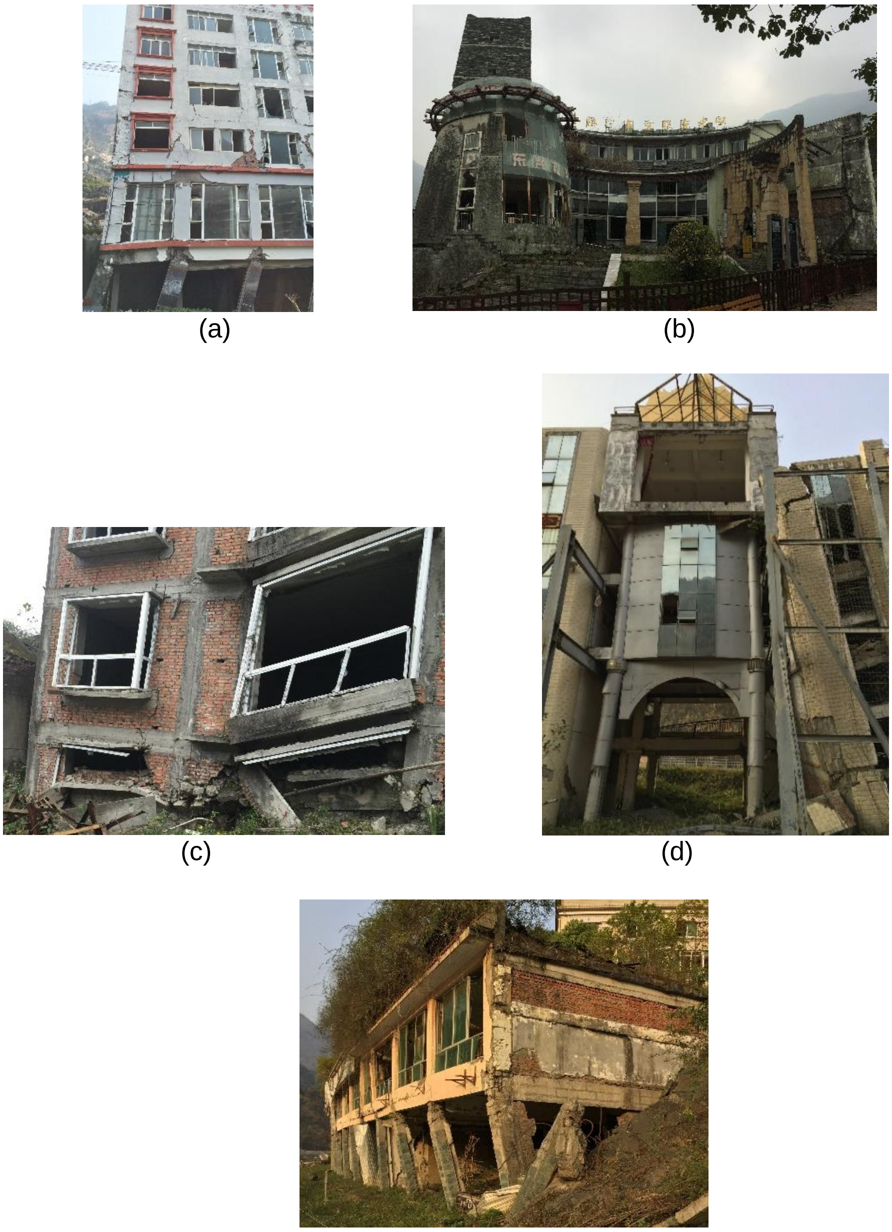
### 6.1.2. Damage assessment scale and extrapolation criteria

Grounding on the review presented in Chapter 2, the adopted damage scale functional to integrate building and district-level resilience approaches is presented in Table 3.1. Both authoritative research approaches [114] and regulatory frameworks are considered. As visible from Table 3.1 the proposed damage scales combines numerical limitations for IDR and qualitative descriptions of the damage, establishing relevant correspondences between the two. The damage of the other buildings in the analysed district is therefore assessed through extrapolation. This is attained by comparing the level of damage undergone by Beichuan Hotel after the optimization (as presented in Chapter 5) and the expected damage to other buildings based on their structural features.

**Table 6.1:** Damage scale addressing earthquake disruption level to RC structures. S: structure, O: openings, I: infills. IDR = Interstorey drift ration, LS = Limit State.

| Damage Index | Description (RC fame buildings) | FEMA 356 | SEAOC Vision 2000 | Eurocode 8 | Calvi (1999) |
|---|---|---|---|---|---|
| D0 | No damage | - | - | | - |
| D1 | S: Negligible damage;<br>I: negligible damage;<br>O: Failure of weak openings | Immediate occupancy IDR ≤ 1% or negligible, transient or permanent | IDR < 0.2% transient Permanent negligible | IDR ≤ 0.5% | Damage ≤ LS1<br>IDR ≤ 0.1% |
| D2 | S: moderate damage;<br>I: infill walls damaged;<br>O: breakthrough of mildly resistant windows. | | IDR< 0.5% transient Permanent negligible | | LS1 < Damage ≤ LS2<br>0.1% < IDR ≤ 0.3% |
| D3 | S: severe structural damage;<br>I: several infill walls damaged or collapsed;<br>O: Failure of strong windows | Life safety IDR ≤ 2% transient IDR ≤ 1% permanent | IDR< 1.5% transient IDR< 0.5% permanent | Chord rotations | L S2 < Damage ≤ LS3<br>0.3% < IDR ≤ 0.5% |
| D4 | S: partial collapse of structural elements and/or roof;<br>I: failure of infill walls. | Near collapse IDR < 4% transient or permanent | IDR< 2.5% transient or permanent | | LS3 < Damage ≤ LS4<br>0.5% < IDR ≤ 1.5% |
| D5 | S: Total collapse of structural elements<br>I: failure of strong infill walls | | IDR > 2.5% transient or permanent | | Damage > LS4<br>IDR > 1.5% |

In order to establish the baseline performance for Beichuan Hotel and as described in Chapter 5, an IDR of 0.5% is adopted for the optimization strategy. Therefore, assuming a damage of D1-D2 on the proposed damage scale for Beichuan Hotel under the same seismic action, it is necessary to establish the criteria for extrapolation. These are represented by specific building features that can increase or mitigate the impact of the hazard.



(a) (b) (c) (d) (e)

**Figure 6.2:** Examples of failure mechanisms in Old Beichuan urban district, including: soft-storey mechanism at the ground floor (a), in-plan and in-height irregularity (b), excessive cantilever elements and scarce anchoring between masonry infills and RC frame (c), presence of non-structural elements and claddings disjointed from the façade (d) and absence or wrong positioning of shear walls (e).

Grounding on building regulations [33, 106] and heuristics, the criteria determining a higher disruption level can be summarized as follows:

- Lack of infills at all levels to avert soft-storey phenomena, such as in Figure 6.2a;
- In-height and/or in-plan irregularity fostering torsional mechanisms, as in Figure 6.2b;

- Presence of cantilever elements detached from the structural frame that could result in an alteration of the building's natural frequency and in the amplification of its oscillations during a seismic event, such as in Figure 6.2c;
- Presence of cladding or façade decorative elements that could detach during a seismic event, such as the building presented in Figure 6.2d;
- Lack of seismic joints for blocks measuring more than 30 m in plan, in any direction;
- Improper design of shear walls or infills, leading to preferential drift directions, such as in the garage block in Figure 6.2e.

In order to allow a comparison of the damage attained in as-built and optimized conditions, it is necessary to establish a methodology for its calculation. The proposed damage scale features 6 levels of damage and as a result it is licit to consider D0 as coinciding with a 0% of damage while D6 would entail a 100% of disruption for the building. Consequently, each step from D2 to D5 would increasingly entail 20% of additional damage compared to the previous level. Equation 6.1b represents the damage discrepancy $\Delta DS_i$ between the optimized scenario ($DS_{i,Opt}$) and the as-built one ($DS_{i,R}$). One performed the calculation for all the buildings in the district, Equation 6.1a provides the damage reduction DR as a simple mean resulting from the ratio between the damage reduction and the number of buildings $N_b$.

$$DR\ [\%] = \frac{\sum \Delta DS_i}{N_b} \quad \text{(a)} \qquad\qquad \Delta DS_i = DS_{i,R} - DS_{i,Opt} \quad \text{(b)}$$

**Equation 6.1:** Damage reduction (DR) formulation (a) and specification for discrepancy of damage state between the real scenario ($DS_{i,R}$) and hypothetical optimized solution ($DS_{i,Opt}$).

### 6.1.3. Multi-dimensional mapping

In order to fully characterize the district in terms of buildings' functionality, infrastructural system and connectivity to nearby urban centres, a thematic mapping of the area was conducted. Namely, over the field investigations abundant photographic material was collected. Based on that, a detailed mapping of the area was performed to establish the correspondence between the satellite imagery and the photographic data. This also allowed to conduct a building-level damage appraisal both in terms of extent and type for each mapped building of Old Beichuan district.

Namely, this entails the considerations of the following domains:

- Road network system and connectivity to other districts;
- Registered damage level, calculated according to the proposed damage scale as in Table 6.1;
- Damage typology;
- Building functionality;

- Construction technology (e.g., reinforced concrete frame buildings, masonry load bearing structures).

Figure 6.3 displays how the proposed multidimensional mapping domains reflect on resilience and on its phases. Namely, the identified resilience phases are coherent with the ones identified in Chapter 2 [71], precisely consisting in: disaster prevention, damage propagation, post-disaster assessment and recovery. In detail Figure 6.3 presents an explicit representation of which aspects are more impacting towards certain resilience phases than others.

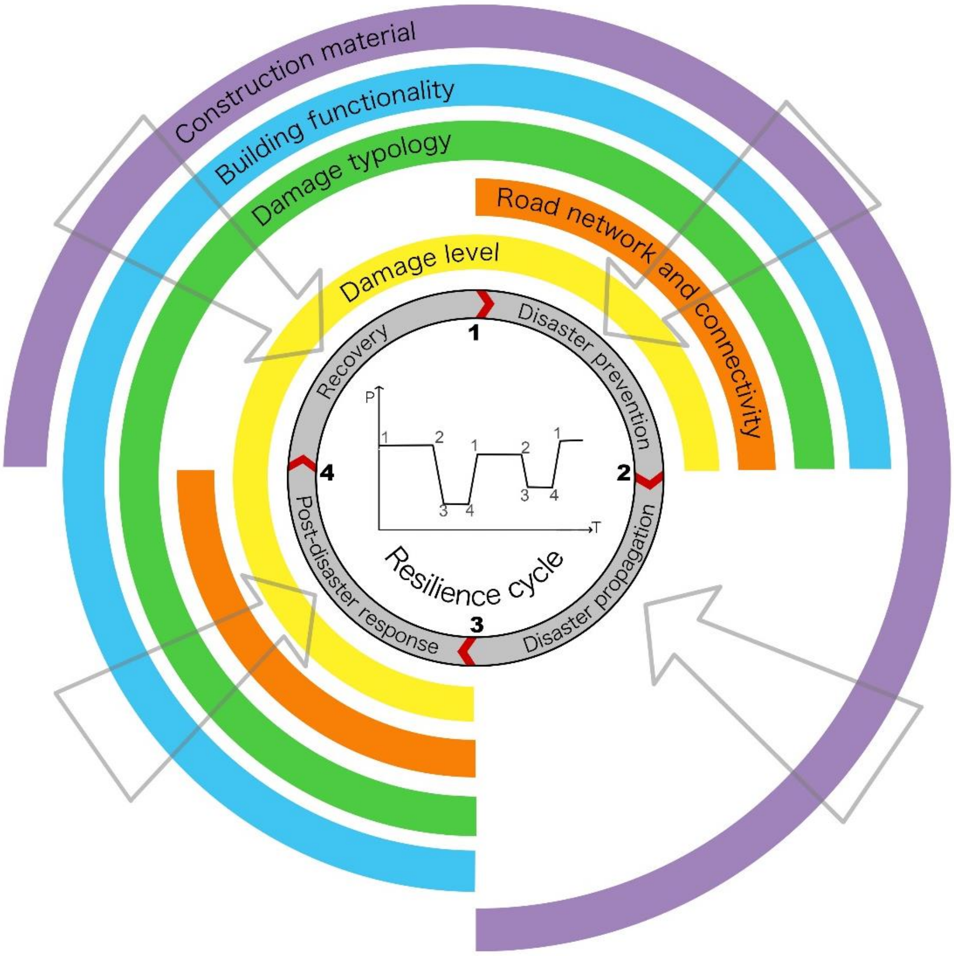


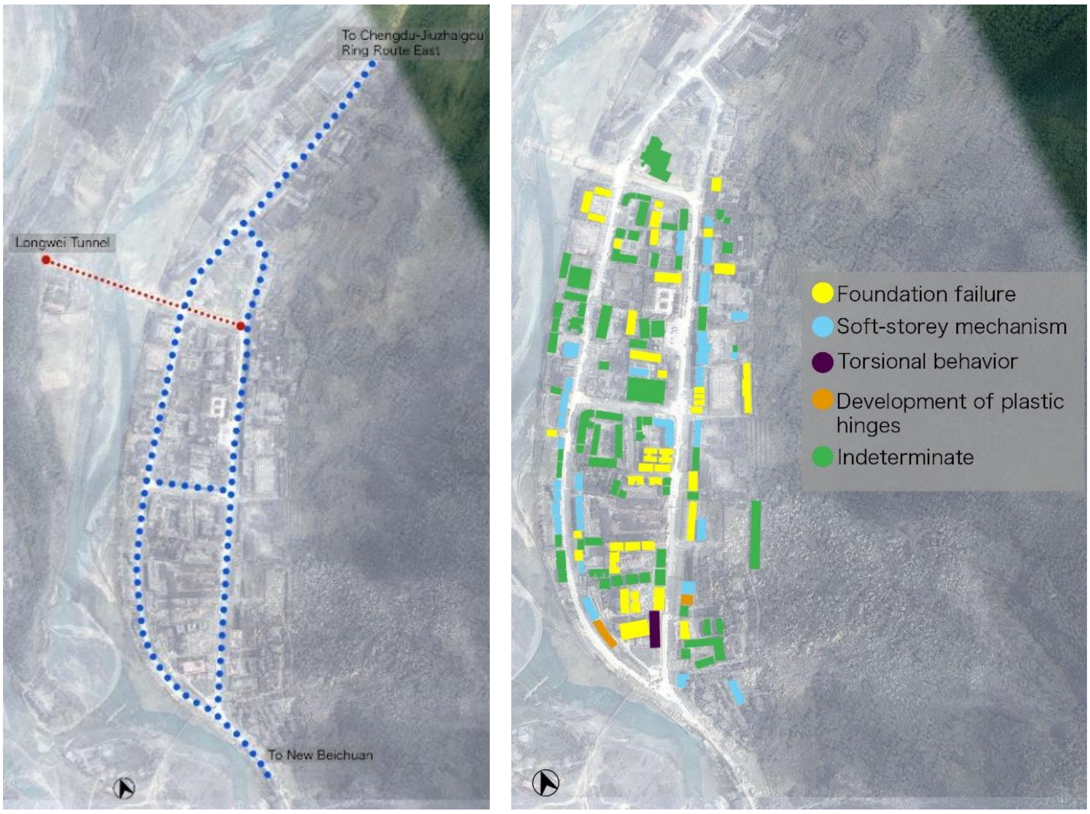
**Figure 6.3:** Interlinkage between resilience and multi-dimensional mapping.

## 6.2. Results

This section is divided in two parts and the first one introduces the results of the district-level mapping based on the previously outlined criteria. The second part of the section outlines the comparison between the damage levels effectively attained by the buildings in the aftermath of the 2008 Wenchuan earthquake and the disruption undergone in the scenario where the proposed optimization strategy is adopted.

### 6.2.1. Multi-dimensional mapping

The characterization of buildings and infrastructures represents a crucial aspect for the resilience of an urban centre in face of seismic hazards. Figures 6.4 – 6.6a feature the mapping of Old Beichuan based on the previously outlined criteria. The infrastructural network appears not redundant in terms of connectivity to other urban centres, as evidenced by Figure 6.4a. Figure 6.4b shows instead a significant percentage of buildings which failure mechanism is indeterminate due to the consistent level of damage. A consistent percentage of buildings appears to have undergone foundation failures, which is a clear flag for the adoption of unsuitable design strategies in combination to a lack of understanding of the local environmental factors.

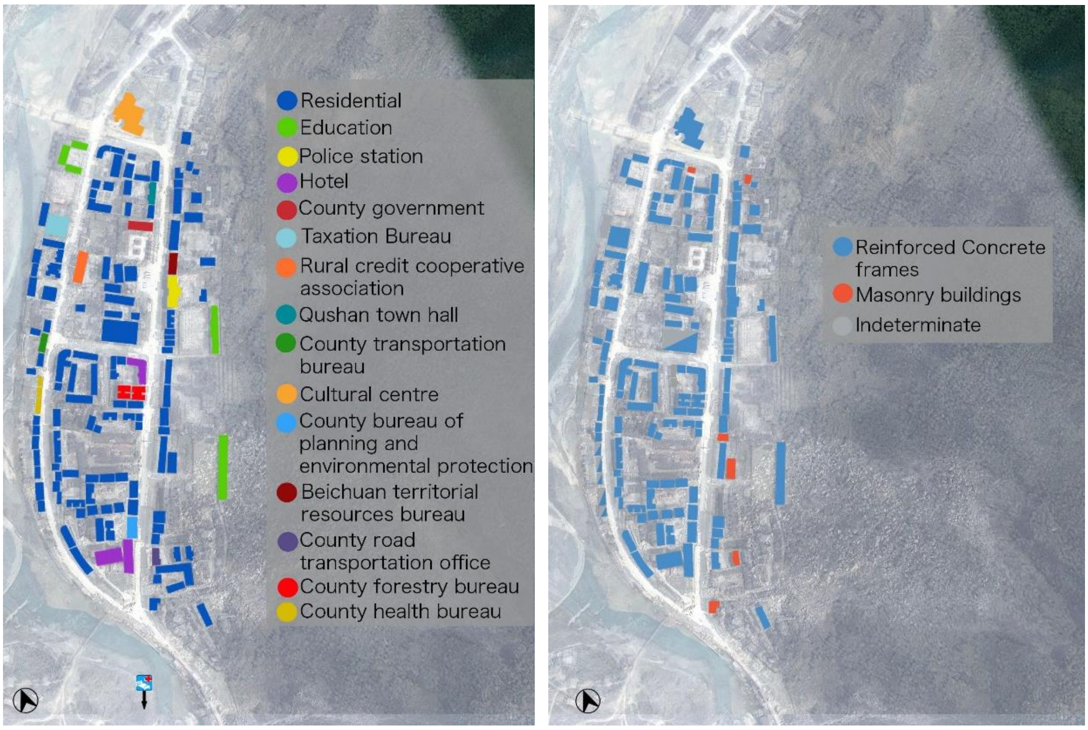


(a) (b)

**Figure 6.4:** Infrastructural connectivity (a) and failure mechanism (b) in Old Beichuan.

It has to be pointed out that Figure 6.4b presents just the prevailing triggering mechanism for the structural failure, albeit in several instances there are multiple causes leading to the final disrupted condition. For instance, a soft-storey failure can result from the combination of (i) lack of infills at a specific storey in the building, (ii) superficial foundation system in coincidence with (iii) soil liquefaction. Therefore, the presence of a large number of structures compromised due to the incompatibility of the foundation system and soft-storey phenomena is a clear evidence of perhaps an unsuitable investigation prior to the design. Another viable option is the potential lack of geotechnical mapping for the area, which would however highlight a negligent consideration of the context as the characterization of the ground properties represents one of most crucial phases in a design process.

Figure 6.5a provides an overview of the functionalities for the Old Beichuan district area, highlighting a clear prevalence of residential buildings. Similarly, Figure 6.5b evidences that RC frames represent the majority of the structures in the district, while few of them could not be characterized given that they had been reduced to debris.



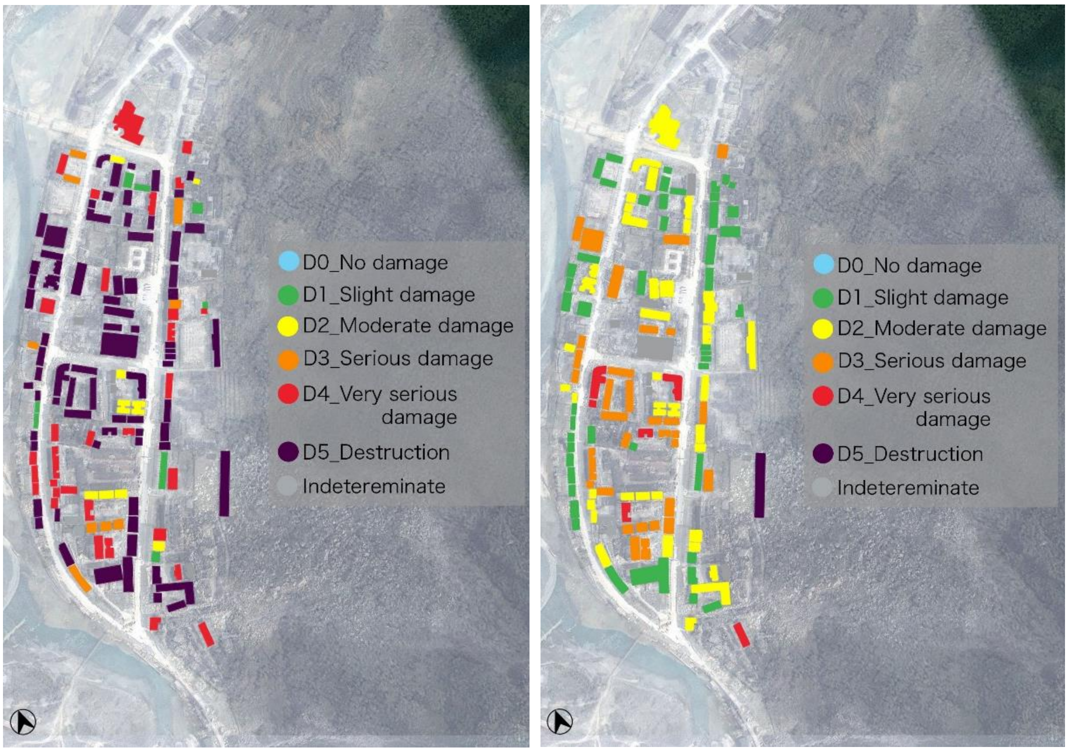
(a) (b)

**Figure 6.5:** Buildings' functionality (a) and construction typology (b) in Old Beichuan.

### 6.2.2. Damage forecasting and reduction

The damage to buildings caused by the Wenchuan seismic event and its comparison with a hypothetical scenario where optimization-based were adopted to enhance the resilience is presented in Figure 6.6. The overall damage reduction obtained through the application of the proposed optimization-informed methodology is evident. Grounding on the methodology presented in section 6.2.3 it is therefore possible to calculate the global damage reduction percentage, which results in almost 40% less compared to the current scenario.

It is pertinent to mention that some structures still exhibit a high vulnerability given their location in proximity of the slope where the rock fall occurred after the main seismic event. To this regard, an equivalent damage level to the real scenario is assigned. In order to avert these secondary events, local consolidation strategies could be adopted. Nonetheless, a preliminary site assessment could have highlighted these vulnerabilities and criticalities leading to devise bespoke consolidation strategies for the rock fall-slope or even considering the relocation of the urban centre.



(a) (b)

**Figure 6.6:** Current damage level (a) in Old Beichuan and predicted scenario with the adoption of optimization techniques (b).

### 6.2.3. Dynamic vs Static resilience

The differentiation between dynamic and static resilience stems in one case from the consideration of real-time data and their absence in the other scenario. When static resilience is addressed, the assessment is performed once and updated on a regular basis in order to provide efficient and effective emergency plans. However, this strategy does not entail the consideration of a system in place able to inform the framework regarding the built environment's performance on a real-time basis, such as what happens in terms on energy management. On the contrary, the pursuit of a dynamic consideration of resilience requires an accurate and almost real-time understanding of the system components' performance. In the case of seismic hazard, this would entail the collection of displacement data for buildings and infrastructures.

However, given the statistical nature of earthquake's occurrence and their forecasting and the current lack of digitalization of our built environment, it is often not deemed as a cost-effective choice to have real-time monitoring systems in place for standard buildings (e.g., residential). Ideally, if both a digital twin of the urban landscape and its components was in place as well as a structural health monitoring system for each buildings and infrastructures, it could be easy to assess on a real-time basis what the current resilience would be.

A dedicated interface could be developed in order to integrate building and district-specific information. As a consequence, one could for instance have access to specifications regarding each of the indicators listed for the district-scale approach in Chapter 4 but also accessing sensor-related information and most important, a real-time update on the serviceability condition of the building.

This would also lead to faster evacuations and allocation of resources and services, with the potential of linking structural health monitoring systems to evacuation signals (e.g., alarms). The integration of structural health monitoring systems at the building level (and ideally not just in critical infrastructures) with alarms would allow a prompt evacuation of the inhabitants as soon as the structure's performance indicator would exceed a pre-defined threshold. If the building collapsed, the system would therefore register it and prompt the information into the framework updating emergency rescue services that a specific route could not be viable as occupied by debris.

Having however acknowledged that several steps are yet to be taken in order to attain such a level of integration, a first step towards a better safeguard of human lives and the built environment would be to equip all the critical infrastructures with structural health monitoring systems. This would consequently avert the jeopardy of key infrastructural networks and services, informing local municipalities and emergency rescue services about the fastest and safest routes to take in case of an access to a site affected by earthquake, but also allowing a better maintenance strategy.

### 6.2.4. Implications for decision-makers and private users

A significant contribution provided by the proposed framework consists in the potential integration with existing policies for disaster management at the district, regional but also national level. This clearly reflects both on the regulatory bodies (e.g., municipalities and governmental organizations) but also on the private building owners.

As section 6.2.3 has highlighted, the level of digitalization needed to fully implement such framework is higher than the one currently experienced in existing urban centres. However, as formerly outlined, a first step towards the integration of this methodology would be equipping critical buildings and infrastructures with structural health monitoring systems. However, the latter have also to be linked to a digital representation of the structure in order to prompt simulations automatically and in an almost real-time way. Given the higher complexity of tasks required to put in place, carry out and supervise such tasks, a new set of professional figures is needed.

These figures reflect what industry currently demands for, namely structural/civil engineers with strong skills in computing and data analysis. This phenomenon is already visible worldwide, with a dramatic and steady increase in data creation and a consequent need for professional figures able to interpret it according to the specific domain of interest.

From an organizational perspective, the opportunity of having an almost real-time picture of the resilience level of the urban centre would allow to expedite the allocation of resources during and after the emergency. In terms of preventive strategies, this would reflect on the opportunity of saving time and resources in carrying out period assessments for building and infrastructures, benefitting the allocation of resources for resilience improvement. Periodic controls and a strict maintenance should also be strategized to ensure the efficiency of the system in place to allow a smooth data flow in emergency conditions.

Similarly to the policies adopted by some countries in terms of incentives towards energy and performance-enhancement strategies for buildings, the same should apply to structural health monitoring systems. At a national level, incentives should be issued in order to equip residential buildings with structural health monitoring systems. As a natural consequence of the huge amount of data generated in relation to these equipment and the scale of their adoption, suitable data-protection strategies should also be put in place to safeguard private users.

It is foreseen that such a system could encounter the higher resistance from realities where the concept of digitalization in the urban context is far from being considered. In the occurrence of integrating such a methodology, small-scale and local urban realities would be perhaps the ones to be challenged the most. Clearly, this observation applies to the reluctance in terms of implementation and not to technical challenges that might be encountered while applying such a system at different scales.

As a matter of fact, large towns would be significantly more demanding to equip but it is likely that previous digital strategies could have already been in place and therefore the proposed methodology would not be perceived as too distant from the state of things. On the contrary, for local realities where paper-based methods are still in place and digitalization is still hindered, this strategy would represent a significant jump resulting is significant efforts for its implementation unless enforced by governmental regulations.

At the district level it is shown in Eq. 6.2 how the overall resilience level $D_{L,R}$ would result from the combination of individual resilience contributions from buildings $B_i$ and infrastructures $Ii$ in the specific urban context. Conversely, at the national level the overall resilience capacity $N_{L,R}$ would correspond to the combination of the single districts and towns $D_{L,Ri}$.

$$D_{L,R} = f(B_1, B_2, \dots B_n; I_1, I_2, \dots I_n) \quad \text{(a)} \qquad N_{L,R} = f(D_{L,R1}, D_{L,R2}, \dots D_{L,Rn}) \quad \text{(b)}$$

**Equation 6.2:** Formulation for district-level resilience $D_{L,R}$ (a) and national-level resilience $N_{L,R}$.

This distinction would be of particular use for policy-makers, who could focus on strategizing resilience enhancement management plans being already provided with a clear breakdown of which categories need bespoke intervention. As an example, one could acknowledge that at a national level the indicator pertaining the redundancy of critical infrastructures (e.g., hospitals) registers an insufficient score for 20% of the towns. Consequently, this would prompt a financial and technical strategy development to attain a satisfactory level of critical infrastructures for the districts whose service provision is this regard appears as insufficient.

At the district level this would instead reflect in the capacity of targeting specific buildings, infrastructures, services or plans registering insufficient performance levels. This would enable a smoother workflow and ideally reduce bureaucratic hurdles if this methodology could be organically integrated in standard practice.

### 6.2.5. Pre and post-earthquake applications

As previously outlined in Section 1.7, the proposed framework provides a twofold benefit in terms of its applicability to both pre and post-disaster phases. Namely, the underpinning motive behind this extensive applicability is due to the twofold articulation of the framework at both district and building scale. Sections 6.2.3 and 6.2.4 extensively outlined the opportunity of integration with real-time monitoring systems and how the framework could benefit the development of standardized disaster management practices, with consequent advantages in terms of time and resource allocation.This links to the applicability of the proposed methodology to pre-disaster conditions, where preventive and proactive strategies have to be put in place to limit the damages in face of the seismic emergency. This is therefore attained at two levels, namely management and technical, which clearly reflect the district and building components of the framework.

In terms of management strategies, this entails building the resilience capacity by strategizing for instance on emergency services in place, continuity of emergency provision (e.g., electricity, water and communications), evacuation plans and planning on how to conduct the building audit in the aftermath of the disaster. As outlined in

Chapter 4 and specifically in Sections 4.3 and 4.4, the proposed framework fosters the development of a consistent resilience capacity drawing on a comprehensive set of indicators representative of district-level resilience. These criteria ground on the definition of resilience and hence they encompass the whole span from pre, during and post-disaster conditions, therefore including as an example environmental assessment elements, monitoring strategies, post-disaster assessments, energy provision but also policy and financial aspects.

At the building level it is possible to adopt the third stage of the methodology proposed in section 5.2 to design new buildings and therefore in a pre-disaster condition, whereas stage 1 can inform investigation of specific building features in existing buildings. In terms of post-disaster, stage 3 could be adopted to investigate the best retrofitting strategy in order to enhance the resilience capacity of a building following to an earthquake.

## 6.3. Discussion

The present Chapter provided an explanation of how the qualitative and quantitative frameworks can be integrated to further enhance disaster management strategies. The integration between the urban-scale resilience framework and building-level optimization would provide the chance to extrapolate the damage assessment from building to district level. A multi-dimensional mapping would provide a twofold benefit in both aiding the identification of the criteria necessary to adopt the urban scale framework, but also providing a qualitative representation of the resilience of a district from the built environment standpoint.

With respect to Figure 6.4 and the proposed maps for Old Beichuan, it is evident how the construction technology is highly relevant throughout the whole resilience cycle, apart from the post-disaster assessment phase. This is due to the fact that the purpose served by the construction technology is functional to ensure the necessary robustness and capacity to endure the hazard, which is therefore relevant in terms of prevention and to limit damage propagation. Similarly, the choices operated during the reconstruction (i.e., recovery) phase have an immediate impact on costs and recovery times, hence influencing the timeline for population relocation into their homes. At the same time, the construction technology will be determinant to establish a new level of performance for future hazards and, preferably, enhance the future resilience level.

On a different note, damage level and typology are tightly connected to the maintenance strategies especially for what pertains the preventive phase. Clearly, a building which is already partially compromised on a structural level will exhibit lower resilience than one in suitable performance conditions. At the same time, the entity and extent of the damage will determine the post-disaster reconstruction after a suitable damage appraisal.

It is also evident how the infrastructural network plays a key role for both prevention and post-disaster response as it enables a smooth evacuation and access of emergency rescue services. This links to one of the main criticalities in Old Beichuan, which relates to the insufficient redundancy of the infrastructural network which prevented emergency rescue systems to access the area and inhabitants to leave dramatically increasing the death toll.

The building functionality is another key factor, as spatially locating strategic infrastructures such as hospital and schools, can aid post-immediate response. Additionally, the identification of strategic infrastructures can help to coordinate urban planners, local governments and designers in order to optimize the spatial location of these buildings in order to ensure a sufficient service coverage in case of disruption.

## 6.4. Conclusion

This Chapter explained how to integrate the building and district-scale resilience frameworks into one workflow and additionally providing a strategy to aid the urban-level framework criteria identification through a thematic mapping of the analysed area. This was deployed on Old Beichuan County, although the urban-scale framework was not applied in this work given the need to perform Analytic Hierarchy Process analysis before. However, this could be entailed by future work opportunities. Nonetheless, the Chapter provided a meaningful validation for the multidimensional mapping strategy which can effectively enhance the identification of built environment-related criteria representative for its vulnerability and resilience.

It was however demonstrated how adopting an optimized performance-based approach can result into a damage reduction of up to approximately 40%. This was attained by scaling up the building-level damage to a district-level adopting a semi-qualitative extrapolation strategy. Although factoring in a certain level of uncertainty given the subjectivity involved in this approach, the damage reduction is still evidenced by the presented results.

The current Chapter as also shown how this framework would benefit policy-makers and private users. Regarding the first, the adoption of a two-scale methodology would allow a faster identification of faults and targets, enabling a leaner and standardized disaster management strategy across districts and nations. At the level of the private building owner, the integration of almost real-time structural health monitoring systems would ensure a higher level of safety and faster evacuation times.

Allowing a more efficient system into standard practice for disaster management would avert dramatic scenarios such as the one occurred in Old Beichuan in the aftermath of the 2008 Wenchuan Earthquake. Besides, given that technologies are available and extensively exploited in terms of research activity, it is time for industry and governments to enforce the adoption of strategies that would allow a better safeguard of human lives.

Overall, it is therefore possible to conclude that the proposed frameworks presents a clear potential for scalability across building and urban-levels. In addition, the opportunity of involving a specific parameter set for each level of analysis lends to the framework a high degree of adaptability. This would result in scale-specific resilience assessments, able to capture the essential aspects in relation to the considered analysis level. Additionally, these considerations close the loop of the considerations formulated in Chapter 2 specifically regarding the identified gap amongst district and building level resilience strategies, providing an applicable approach to resolve this issue.

# 7. Conclusion and future work

This Chapter provides a final analysis of the work conducted to answer the research questions stated in Chapter 1. Stemming from the main findings for each research question, a discussion in relation to the initial hypothesis will be provided. Additionally, further insights will be outlined regarding the limitations observed during the development of the research.

## 7.1. Main research findings

The current section presents an outline of the main achievements attained regarding each of the research questions presented in Chapter 1. These were devised to assess the truthfulness of the pertinent research hypothesis as stated at the beginning of the Thesis. Grounding on the findings related to each research question, the concluding remarks for the research hypothesis will be formulated. .

### 7.1.1. Urban-scale disaster resilience management

The present section refers to research question 1, which can be restated as follows:

*Can a disaster management framework be developed to address buildings' resilience at the district level with a holistic consideration of related factors?*

The first research question mainly addressed the qualitative side of the proposed resilience framework, tackling resilience from a district-level perspective. Given the scale of the analysis, the resilience of the built environment in face of geo-environmental hazards was tackled from a mostly technical-organizational perspective. A preliminary review of resilience as a theoretical concept and consequently of its applications in terms of disaster management frameworks was conducted. A main distinction between research and institutional frameworks was attained and major differences were highlighted. Specifically, amongst the strengths of the analysed research frameworks there are a higher level of focus for target of resilience and the ability of capturing technical aspects often neglected by some of the institutional frameworks. The latter in fact tend to widen the scale of the analysis attempting to include a wide spectrum of hazards and resilience targets, becoming more suitable for assessments at the community level rather than for technical purposes.

Building upon the review it was demonstrated that an advantageous technique to develop urban-district resilience framework consists in establishing a series of relevant domains (e.g., infrastructures, emergency services, governance and environment) featured by a set of criteria. The validation of the criteria was performed using a Delphi-based expert consultation that existing research proved to be effective in collecting feedback from both the academic and industrial communities. The indicators were thoroughly revised and improved following to the collected feedback highlighting a prevailing agreement regarding the relevance of energy and infrastructure-related indicators over the urban fabric ones. A certain level of disagreement was unexpectedly detected in relation to indicators such as geotechnical investigations and the overall understanding of local environmental conditions.

A representative contribution to this research question was also provided by Chapter 6, where the qualitative and quantitative frameworks were combined in order to factor different set of analyses scales, each with their own specific set of variables, suitable to the level of the assessment. Namely, it was demonstrated how a district-level resilience assessment can be pursued adopting a qualitative framework such as the proposed one, which can be systematically informed by the building-level analyses conducted by means of the quantitative approach.

As a result of the above, it can be observed how the first research question as stated at the beginning of this section can be considered fulfilled as results evidence that a disaster management framework has been developed and the research gap regarding the micro and macro-scales disconnection has been bridged.

### 7.1.2. Investigation of building features adopting optimization techniques

This and the following two sections relate to the quantitative resilience framework as they correspond to the three research stages identified in Chapter 5. With respect to this section, the pertaining research question is the following:

*How can structural design parameters be inferred to accurately characterise and model a seismically compromised building in case of limited access to data and lack of supporting documentation?*

The extensive literature review presented in Chapter 2 highlighted an evident gap in the reviewed body of knowledge in relation to the current disconnection amongst optimization strategies and commercial software. It was demonstrated how in most cases the optimization and the structural behaviour simulations are either carried out in the same tool (e.g., MATLAB), or in different tools but disjointed from each other. This proved to be highly inefficient given the lack of flexibility of such methodologies, which cannot fulfil the demand for different structural behaviour analyses. In addition, exploiting the strength of a software might be more advantageous than using another one to perform a task that has not been designed for.

Furthermore, as showed in Chapter 5, the characterization of unknown building features is usually burdensome, and it entails a series of systematic tasks in addition to the access of reliable design documentation. However, as discussed in Chapter 5 in relation to REACH, physical documentation can be not accessible or sometimes it might not even exist when a building's construction date goes too far back in time and it is not considered historical heritage.

To overcome this issue, the review highlighted an extensive adoption of machine learning techniques in relation to structural engineering, although the most common deployment of genetic algorithms addresses the design purpose. In this case however, and specifically pertaining the second research question, the potential of GA was exploited to infer the value of specific building features which could not be assessed during site investigations. This was attained by exploiting the potential of the integration between MATLAB and Autodesk Robot and iteratively invoking the latter via COM-based API from MATLAB. The objective function for the GA was the minimization of the discrepancy between the effective EDP and the one attained through the simulation. The GA simulations were iterated for a total of 30 generations with each 80 individuals.

The literature review highlighted two main EDPs, namely node displacement and inter-storey drift ratio (IDR). During this stage it was observed how the node displacement obtained approximately 3% more accurate results than the IDR.

Different scenarios were devised based on the most common damage typologies highlighted in review phase and bespoke GAs functions were developed to perform targeted investigations and hence finding the most likely value for the variable featuring each of the scenarios.

The deployment of this technique on the case study building of Beichuan Hotel provided a validation for the methodology given the highly accurate results attained. It is therefore possible to conclude that the research question posed at the beginning of this section was extensively answered and fulfilled based on the work carried out in Chapter 5 and specifically in relation to the first research stage (i.e., Stage 1).

### 7.1.3. Identification of influencing building features for structural stability

The third research question can be restated as follows:

*Can the governing variables most sensitive to the structural integrity of a building be inferred taking into account a wide range of considerations, including local environmental and geotechnical conditions?*

As previously alluded to, this section refers to stage 2 of the methodology proposed in Chapter 5 and to the related research question. The problem posed herein entailed the identification of the most influencing building features contributing to structural stability in face of seismic hazards. In order to identify a valuable strategy for this purpose, the review highlighted an extensive adoption of sensitivity analysis and PCA techniques in combination with each other. In order to perform sensitivity analysis, in fact, 1000 simulations were conducted to ensure a good variability to the dataset. The variables to be collected at each iteration were identified over the literature review and selected based on the author's experience. The aim of this stage was to adopt a top-down strategy starting from a wider range of variables and utilize an algorithm to aid the selection of the most influencing ones based on the value of the EDP (i.e., performance indicators).

The sensitivity analysis matrix has been processed with PCA in order to identify the PCs which variability was representative of at least 99% of the whole dataset based on the cumulative variance. The total amount of PCs identified were 12 and accounted for 99.6% of the overall variability. The data transformed into PC space have been then used to train an ANN. Based on the extensive literature review proposed in Chapter 2, it was demonstrated how the adoption of ANNs is widely established in the domain of structural engineering and vibration analyses, particularly with the aim of performing damage prediction but mostly in conjunction with FRF techniques. However, it is meaningful to underline how the adoption of these techniques is not jointly conducted, but generally different research consider different objectives. Namely, optimization was not found to have been coupled to damage prediction and investigation purposes. In this work an ANN was trained on software simulations data in order to eventually replace the latter during the last phase of research work.

In order to identify the most performing ANN, a set of 11 ensembles was created adopting a trial-and-error approach adjusting the number of hidden layers and the neurons accordingly to avert overfitting. To do so, the complexity of the ANN's architecture was increased but the number of neurons per layer was reduced and the best performance was attained for a 4-layer feedforward backpropagation neural network. Results evidenced that the node displacement-ANN was significantly outperformed by the IDR-ANN and this was demonstrated by the accuracy of the values attained in terms of investigated variables, but also observing training and test performances. The ANNs were validated adopting the same variables for the scenarios in stage 1, for consistency.

The advantage of this strategy lies in the opportunity of significantly reducing the amount of data generated by the simulations, being able to pick only those which are representatives for the whole trend of the dataset. PCA is crucial as it allows to train the ANN that is then adopted over the ensuing research stage, however it could be replaced with any other dimensionality reduction strategy if needed.

However, a drawback of PCA consists in the impossibility of explicitly acknowledging the governing variables, as the algorithm operates in terms of principal components. It is therefore always necessary to adopt the coefficient matrix to move from the transformed space to the original variable space. Despite this drawback, PCA proved to be effective as the resulting ANN selected for the validation stage exhibited an impressive accuracy of over 99%.

In light of the above and given the successful results provided by the ANN, the IDR was selected as an EDP for the ensuing research stage. Based on the presented results it is possible to conclude that starting from a wider set of variables deemed as influencing for the seismic resilience of a structure, it is possible to select the most impacting in a systematic manner. This does not hinder the quality of the results, but on the contrary it enables a smoother transition between traditional structural software and neural network implementation. Building on these considerations, research question 3 has been extensively answered.

### 7.1.4. Performance-based structural optimization and damage forecasting

The fourth research question is the following:

*Can these sensitive variables inform the development of less computationally demanding structural analysis models with a view to optimize the structural design of a building?*

The review devised in Chapter 2 highlighted a research gap in the utilization of neural network ensembles and, as also mentioned in the previous section, machine learning is mainly adopted for individual tasks. Therefore, it was observed how optimization and damage forecasting are not coupled in the same tool, and a similar consideration can be applied to investigation purposes. This last research question represents the final research stage, where the ANN trained during stage 2 can replace the structural simulation engine and provide performance-based damage predictions.

The ANN is coupled to a GA that, similarly to stage 1, iteratively invokes the simulation tool. However in this stage, Autodesk Robot is replaced with the ANN with considerable simulation time reduction. In fact, whereas in stage 1 an average simulation took about 45-50 s, here the whole optimization process takes less than 2 minutes. Moreover, the GA has been set for a total of 50 generations with 200 individuals each. The number of generations was not increased significantly given that the convergence of the algorithm was observed between 10 and 15 generations, regardless of the population size.

Two ANNs were eventually adopted, one designated to provide reinforcement areas while the other neural network provided frame and mechanical properties for frame and infills. Based on the regulatory frameworks review outlined in Chapter 2 and the corresponding IDR values, 6 damage levels were identified. The benchmark values of IDR for each damage level were then adopted as a performance target for the ANN to analyse a series of frame related features in order to evaluate the advantage of this approach over the effective building configuration. As a result, it was demonstrated how compared to the real-scenario 2% IDR (i.e., damage level 4), a consistent damage reduction could have been attained for instance aiming at a 0.5% IDR (i.e., D1/D2) with an approximate cost increase of 20% using the actual building as a baseline condition. The cost was assessed in terms of concrete volume based on the frame section values calculated by means of the ANN.

The reinforcement ANN was instead functional to calculate the steel reinforcement areas for the most stressed element in the storey registering the highest IDR. Compatibly with the disrupted building configuration, the storey exhibiting the highest deformation appears to be the first one and the column appearing as the most stressed is not the one in the junction between the two block having different elevations, although the latter shows the highest fluctuations in terms of shear demand. Having also characterized, based on site investigation, the column at the junction in terms of reinforcement areas (i.e., longitudinal and shear), it was therefore possible to compare it with the one designed with the aid of the proposed approach. By means of the two ANNs and the GA, the frame geometry was derived and consequently also reinforcement areas. Coherently with field inspection, the as-built configuration presented a significant deficiency in terms of reinforcement although complying with Chinese building codes. On the contrary, the reinforcement areas provided by the ANN appears to be approximately double the as-built provided reinforcement area. This is line with what one could expect as thin reinforcement bars such as φ12 or φ14 often turn out to be inadequate in seismic conditions. This stems from the tendency of modern building codes to often lead to a precautionary over-dimensioning of the structure and significantly high reinforcement areas. Therefore, adopting such thin diameters would create a bar density in the section that would hinder the installation of reinforcement bars and significant difficulties when having to manage starter bars for new storeys and create the proper overlapping.

In addition to the above it is relevant to highlight how the ANN is generally building-specific and it might have to be re-trained when addressing a different structure. Nonetheless, when dealing with recurrent building typologies, it is possible to identify a modular structure and it is often the case of equivalent internal layout, hence loading conditions. Having said that, the same ANN could be adopted when buildings complying with the above conditions are analysed. This would consequently increase the scalability of the approach, especially in its integration with the qualitative framework.

Overall, the presented framework is already fully scalable. It is in fact possible to exploit the full potential of the proposed methodology by integrating it with any commercial structural simulation tool, as long as an API is available. Clearly, the API-specific coding language has to be adopted but the real advantage lies in the adoption of the methodology. Results evidence that the proposed optimized performance-based approach can enhance traditional structural design benefitting the overall seismic resilience of the building. It was also demonstrated that a building which design complies with regulatory framework can undergo significant damage not guaranteeing safeguard of human lives. In addition, the opportunity for damage reduction was proposed in conjunction with an esteem of cost reduction, showing that a bespoke adoption of intelligent techniques can aid a better allocation of resources and enhance seismic resilience. Based on the above considerations, it can therefore be concluded that research question 4 has been extensively answered.

### 7.1.5. Revisiting the hypothesis

The hypothesis as initially formulated in Chapter 1 is as follows:

*Conventional performance-based regulatory frameworks for seismic design do not always sustain the resilience demand and are disjointed from district-scale resilience management strategies.*

The presented research features a two-level approach, at the building and district-scale and it aims at seismic resilience enhancement with the scope of bridging the gap between them. An initial review of meaningful research highlighted the persistence of a significant separation amongst the micro (i.e., building) and macro (i.e., district) approaches. Whereas the building-level methodologies feature a high detail of structural analysis adopting analytical techniques and mainly seismic performance-based approaches, district-level frameworks tend to target an organizational perspective of resilience.

The proposed research therefore articulated in two main research threads but with the aim of linking them together in order to bridge the existing gap across the identified scales. The qualitative approach adopted a Delphi-based expert consultation to develop a framework for disaster management resilience at the district-level, whereas the quantitative research thread featured the deployment of machine learning techniques.

Specifically, a bespoke review of some of the most authoritative research approaches and regulatory frameworks in terms of seismic design was conducted to highlight current performance benchmarks for RC structures. At the same time, a set of increasingly complex ensembles was devised to utilize deep learning and evolutionary computing to provide a leaner approach to designers for investigation, design and optimization of structures in face of seismic hazards. Specifically, research questions 2, 3 and 4 were key for guiding the research work towards the demonstration of the, sometimes, inadequacy of traditional regulatory approaches. In fact, the case study proposed in Chapter 5 proved that even though regulatory compliance is attained, a building can still undergo a damage level such to consistently endanger human lives, which is against the main scope of buildings' design.

Chapter 6 eventually proposed how the two scales of analysis can be combined together in order to inform designers, local governments and institutions in relation to the most impacting factors for disaster resilience and what to target to enhance it. By combining the two scales of analysis, it is possible to adopt a systematic approach to assess and/or enhance seismic resilience at the building-level and consequently scaling up to the district-level. This demonstrates how such approach exploits at the maximum potential the features of each scale, allowing a comprehensive consideration of the built environment's resilience from a both technical and organizational perspectives. As a result, and building upon the presented considerations, it can be observed how the research hypothesis is verified.

## 7.2. Contributions to the Body of Knowledge

This section will outline the main contributions attained by the research work and they will be presented according to the pertaining analysis level. These namely will address building and district-level strategies which were respectively targeted in Chapters 4 and 5. However, contributions from the combinations of the two are also outlined building upon the work presented in Chapter 6.

**Contributions at the district-level:**

- Providing a framework able to target the geo-environmental resilience of the built environment from a both a technical and organizational level;
- The consideration of context-specific features disregarded by other frameworks (e.g., urban morphology), would enable the adoption of GIS techniques integrating the potential for automation;
- Developing a methodology suitable for integration with building-scale approaches in order to bridge the gap between the two levels;
- Devising a tool able to enhance resilience management strategies throughout prevention, disaster propagation and recovery developed factoring in the shortcomings of current approaches.

**Contributions at the building-level:**

- Developing a scalable and generic approach suitable for both new and existing structures with the consequent applicability for risk-based design and for the purpose of pre and post-disaster assessment;
- Applicability in a pre-disaster phase through the installation of performance monitoring strategies for building and infrastructures, but also to design buildings informed by a comprehensive understanding of risk.
- In post-disaster conditions, buildings can be promptly investigated and the most suitable retrofitting strategy can be analysed.
- Given the cyclic nature of resilience, the framework would inform also reconstruction strategies, hence addressing new constructions, when existing buildings have failed to withstand the disaster;
- Provision of a methodology concretely employable by engineers given its integration with commercially established structural software;
- Devising a powerful tool for engineers to overcome the hurdles resulting from often time-consuming bureaucratic procedures and potential lack of documentation, but also advancing structural surveying techniques;
- The development of a methodology that can be combined with other disciplines (e.g., architecture) thanks to the awareness of current software adoptions trends in the profession and coherent with a holistic consideration of design and post-disaster appraisal of a structure;
- Implementation of recent advances in computational structural analysis and structural engineering analyses strategies factoring in augmented machine learning techniques.

**Contributions of the integration of building and district-level approaches:**

- Twofold consideration of built environment resilience and development of a framework for its simultaneous enhancement at the district and building-level;
- Potential for scalability and systematic integration of macro and micro approaches for a comprehensive consideration of resilience, factoring both technical and organizational perspectives;
- Opportunity of integrating the framework with structural health monitoring systems in order to provide an almost real-time resilience assessment of the district;
- Possibility of scaling up this approach at national level and achieving a standardized strategy for disaster management in face of seismic events;
- Potential integration with early warning systems to prompt evacuation when a performance threshold is exceeded;
- Fostering urban digitalization through the integration of technologies involving semantics, point cloud data, real-time analyses and data-enrichment;
- Devising a tool with the potential of assessing the resilience of an as-built scenario, but also evaluating its enhancement which would advantage governments and stakeholders in the development of emergency plans.

## 7.3. Limitations and Future Work

This section addresses some limitations of the presented work which have been observed while conducting the research. Namely, these limitations could be addressed in future work as it will be explored more in detail further on in this section.

With respect to the building-scale methodology a series of assumptions were formulated for instance in relation to the density of masonry, which was assumed as constant when performing the optimization. As presented in Chapter 5, the linear distributed load on the beam due to the masonry infill for two subsequent iterations was calculated based on the ratio between the infill thicknesses for the same iterations assuming the density constant. However, this could be improved by targeting specific masonry density according to the purpose of the optimization and to the producer. In addition, the constraints for the loads investigation as presented in Chapter 5 and in relation to the scenario 4, were established based on the case-study and therefore the values were fetched in pertinent Chinese regulatory framework. However, this could be further generalized or targeted according to a different site where the typical construction material present diverse mechanical properties.

Furthermore, the consideration of cost was operated in a proportionate way based on the volume of concrete utilized, therefore in terms of relative percentage discrepancy referred to the baseline represented by the as-built structure configuration. An interesting opportunity for future work could entail the development of both frame and masonry infills (but not exclusively) in the pertinent ANN, as well as the reinforcement, being coupled to a separate GA which would provide a cost optimization in addition to the current performance-based one where cost is a secondary objective and the building performance is prioritized.

As far as the dimensionality reduction phase is concerned and coherently with the considerations made in Chapter 2, it could be interesting to adopt more modern and nonlinear algorithms, such as KPCA, which have also proven to be effective although PCA is still perhaps the most established. In terms of advantages, the adoption of a nonlinear technique could allow to find better interrelations between the data and perhaps reducing the number of representative PCs to account for the initial dataset variability. Therefore, a lower number of PCs would benefit the ANN training and consequently further advantaging the simulation and optimization time.

Another limitation that can be highlighted regarding the building-scale methodology pertains the assumption made in Chapter 5 about the consideration of the superstructure only. This guided the choice of the case-study building to one that was not compromised at the foundation level. Future work could instead encompass a more comprehensive consideration of geotechnical parameters and the inclusion of differential settlements due to failure at the foundation level and a subsequent optimization.

A valuable opportunity for future work would also entail the application of this approach to strategic infrastructures such as bridges and viaducts. It is renown in fact that their maintenance strategy is key to ensure a reliable performance level across their service life to avert sudden failures and consequently endanger human lives. It would therefore be a meaningful opportunity to extend the application of this strategy to infrastructures perhaps also considering the integration of real-time monitoring systems (e.g., sensors) in order to attain an almost real-time damage forecasting strategy.

On a different note and referring to the district-level approach, it is pertinent to observe how Chapter 6 did not provide a full validation of the Delphi-based resilience framework presented in Chapter 4. However, this could be addressed in future work following to an AHP analysis to identify the hierarchical relevance of the scored indicators.

## 7.4. Final Remarks

The research thread of the work presented in this Thesis encompassed resilience both at the building and district level in face of seismic hazards and specifically targeted the built environment. The work stands out compared to traditional approaches given the adoption of an integrated, scalable and generic approach that integrates a holistic consideration of the physical system (e.g., buildings and infrastructures) with recent advances in computational structural analyses and performance-based seismic engineering. It was therefore demonstrated how challenging regulatory frameworks is sometimes necessary in order to enhance the seismic resilience of structures.

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