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REEBUILD Integrated Techniques for the Seismic Strengthening and Energy Efficiency of Existing Buildings

Overview of seismic and energy retrofit technologies for existing buildings

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REEBUILD

Integrated Techniques for the
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Foreword

Our buildings are ageing, posing an urgent need for renovation to align with the goals of multidimensional European and international policies. The built-up area in Europe covers 25 billion square meters, 10 billion of which were constructed before 1960 and 20 billion before 1990. It is worth noting that 40 % of the European Union (EU) building stock is located in seismic prone regions and was built without modern seismic design considerations. Apart from Member States with moderate and high seismic risk, such as Greece and Italy exhibiting a severe impact (i.e. fatalities, injuries, and economic losses) from earthquakes during the last decades, attention should be drawn to regions with lower risk, e.g. in France and Spain. At the same time, buildings stand out as one of the most energy consuming sectors, therefore having a negative environmental impact. In fact, buildings are responsible for 40 % of EU energy consumption and 36 % of the EU total CO_2 emissions, whereas 75 % of the EU existing building stock is considered energy inefficient. The highest amount of energy use in buildings derives from the operational stage of their life time (e.g. heating, cooling), resulting in a significant source of carbon emissions with detrimental effects on climate change.

Notwithstanding this negative impact, the building sector provides a unique opportunity to create, through risk-proofed renovation, a safe, sustainable, and resilient built environment which promotes wellbeing and economic growth, and ensures that EU energy and climate targets are met. In this context, the European Parliament entrusted the European Commission’s Joint Research Centre with the two-year pilot project “Integrated techniques for the seismic strengthening and energy efficiency of existing buildings” or REEBUILD.

REEBUILD aims to define technical solutions that can reduce seismic vulnerability and increase energy efficiency of existing buildings, at the same time and in the least invasive way. Thereby, increased earthquake resilience and limited environmental impact of buildings is sought by protecting life, economy and the environment. The project has the following key-objectives:

- Define the tools and guidelines to reduce, all at once, vulnerability and energy inefficiency of buildings.
- Stimulate the use of integrated solutions.
- Create awareness about the topic in the aim of prevention.
- Increase resilience of the built environment to seismic hazard and climate change.

The geographical scope of the project covers EU seismic prone regions. However, all EU citizens are potential beneficiaries of the project since it can easily be extended to all EU regions considering the ageing of existing buildings and other hazards, including extreme climatic events.

In a policy context, REEBUILD provides scientific advice to support the development of an action plan, which shall supplement existing European Union policies and initiatives in the field of buildings’ renovation. Crucially, the European Green Deal (COM(2019) 640) emphasises the need for a Renovation Wave (COM(2020) 662), supported by the New European Bauhaus ([1]) (COM(2021) 573) to create sustainable, inclusive and beautiful living spaces. The plans to put the European Green Deal into effect further contribute to the economic recovery following the COVID-19 pandemic. In the Energy Performance of Buildings Directive (Directive 2018/844) and the recent proposal for its revision (Proposal COM(2021) 802), besides reducing greenhouse gas emissions, measures related to seismic risk and fire safety are encouraged for planning long-term renovation strategies. The implementation of clean and circular economy principles for the construction sector to achieve a climate-neutral society by 2050 are stressed in the new Circular Economy Action Plan (COM(2020) 98) which also addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The new idea for a holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention measures and the integration of risk reduction and cohesion policies. Likewise, the Action Plan on the Sendai Framework (Commission SWD 2016/205) encourages investment in disaster risk reduction, integrating "Build Back Better" principles for a more resilient built environment. The European Framework for Action on Cultural Heritage (Commission SWD 2018/491), emphasises the need to safeguard cultural heritage against natural disasters and climate change, and relevant measures are encouraged when planning long-term renovation strategies and national disaster risk reduction strategies. The above policies and initiatives contribute to the implementation of the 2030 Agenda for Sustainable Development ([2]) (UN, Resolution 2015/A/Res/70/1) and the Sustainable Development Goal (SDG) 11 “Make cities and human settlements inclusive, safe, resilient and sustainable”.

([1]) New European Bauhaus, https://europa.eu/new-european-bauhaus/index_en

([2]) Sustainable Development Goals (SDG) Policy Mapping tool, https://knowsdgs.jrc.ec.europa.eu/intro-policy-mapping

Integrated retrofitting of existing buildings can be seen as a nexus between policies improving the disaster resilience of the EU, encouraging the energy renovation of buildings, promoting circularity within the building sector, and protecting cultural heritage.

Several activities were foreseen to achieve the REEBUILD objectives. EU buildings requiring upgrading were identified, and existing seismic and energy retrofit technologies were assessed in a life-cycle perspective. Combined retrofit solutions were explored based on available technologies and recent scientific developments in the field. A simplified method for the assessment of the combined upgrading was proposed and applied to case studies of representative building typologies retrofitted with the identified solutions. Seismic risk and energy performance of buildings along with socioeconomic aspects were assessed at regional level throughout Europe. Such regional assessments were used to identify appropriate intervention scenarios based on their regional impact and highlight the regions where interventions are of higher priority. National, regional and local authorities, industrial associations and expert communities were involved in enquiries and discussions of relevant implementing measures (legislation, incentives, guidance and standards), technologies and methodologies for the combined upgrading of existing buildings. Dissemination and outreach is further supported by reports, a web platform and public communication material. REEBUILD activities were organised in five main actions:

1. Overview and classification of technologies for seismic strengthening and energy upgrading of existing buildings
2. Analysis of technologies for combined upgrading of existing buildings
3. Methodologies for assessing the combined effect of upgrading
4. Regional impact assessment and contributions to an action plan
5. Stakeholders' engagement.

This report provides a synopsis of the main results carried out within Action 1, briefly identifying the EU building typologies most needing a combined seismic and energy retrofit, as essential step to facilitate the selection of seismic and energy retrofit technologies. The most common seismic and energy retrofit technologies are reviewed and classified to assess their applicability to the investigated building typologies in terms of cost, disruption time, and compatibility. This report mainly targets policymakers, thus it provides a summary of the main results of the above-mentioned aspects by simplifying technical details. However, specific technical aspects on the identification of building typologies needing combined retrofit can be found into the corresponding JRC technical report (Romano et al., 2023).

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Abstract

The renovation of the EU existing built environment to make it more energy-efficient and less carbon intensive over its entire life cycle, as emphasised by the Renovation Wave strategy within the European Green Deal, assumes a key-role to meet the ambitious goal of a climate-neutral society and economy by 2050. However, the European existing building stock, mainly located in seismic-prone regions, also suffers from seismic vulnerability leading to detrimental social, economic, and environmental impacts in case of an earthquake. Hence, it is essential to boost integrated renovation interventions aimed at simultaneously enhancing the seismic and energy performances of buildings to effectively achieve a safe, resilient and sustainable building sector.

This report provides a simplified analysis for identifying the EU existing buildings most needing combined seismic and energy retrofit, along with a focus on the Italian context due to the huge variability of its building stock. This investigation is essential to facilitate the selection of suitable renovation strategies, useful for practitioners, policy makers, and local authorities. Technologies for seismic and energy retrofit are reviewed and classified to assess their applicability to the investigated building typologies mainly in terms of compatibility, cost, and disruption time to ease the decision making process of different stakeholders, such as investors, clients, policymakers, in the preliminary phase of a renovation design.

Executive summary

The EU existing building stock, considering both residential and non-residential segments, accounts for 25 billion square meters of built-up area (BPIE, 2011), of which 20 billion erected before 1990, thus representing an ageing built environment compliant neither with the recent EU energy efficiency regulations, nor with modern seismic design code requirements (i.e. Eurocodes). The achievement of an energy-efficient built environment by boosting renovation solutions for obsolete buildings is a high-priority issue for Europe, as it represents not only an effective key to meet the EU ambitious energy and climate targets by 2050, but it can also generate economic and social benefits, fulfilling the sustainable development principles. At the same time, these ageing buildings need to satisfy structural safety and reliability requirements both in ordinary and exceptional conditions (e.g. in case of seismic events), to prevent both extensive structural and non-structural damages along with consequent considerable economic losses, fatalities, and environmental impacts. Hence, a successful and cost-effective building renovation solution should not be exclusively energy/environmental goal-oriented, but it should deal with integrated seismic and energy retrofit interventions to achieve a safe and sustainable built environment over time.

The pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD, financed by the European Union (EU) under decision C (2019) 3874-final of 28 May 2019, was launched to put forward a simplified holistic approach to enhance simultaneously the seismic safety and energy efficiency of the existing European building stock and to stimulate the use of integrated solutions in a life-cycle perspective. In this context, it is crucial to provide a portrait of the EU building stock to identify potential buildings most needing seismic and energy upgrading, as basis to proceed with the selection of effective retrofit technologies. Technologies for seismic and energy renovation are explored to assess their applicability to the investigated building typologies mainly in terms of compatibility, cost, and disruption time to ease the decision making process of different stakeholders in the preliminary phase of a retrofit design.

Policy context

The integrated seismic and energy upgrading of existing buildings supports and creates a nexus among several EU policy goals related to green transition, industrial strategy, disaster risk reduction, and protection of cultural heritage, according to the scope of REEBUILD project.

The European Green Deal (COM(2019) 640) emphasises the need for a buildings' Renovation Wave (COM(2020) 662), supported by the establishment of the New European Bauhaus initiative (COM(2021) 573) to bring the European Green Deal closer to people's minds and homes. Within this policy framework devoted to the ecological transition, the energy renovation of buildings is envisaged as a fundamental step to be also enforced at legislative level by the proposal of the revision of the 2018 Energy Performance of Buildings Directive (Directive 2018/844, Proposal COM(2021) 802) outlining measures Member States should take to at least double the annual energy renovation rate of buildings by 2030 and to foster deep renovations.

Building renovation also supplements the EU industrial strategy through the principles of the New Circular Economy Action Plan (COM(2020) 98), one of the main blocks of the European Green Deal, stimulating resource efficiency and life-cycle thinking approach for several sectors to achieve a climate-neutral society by 2050, as legally enshrined by the European Climate Law (Regulation 2021/1119). As for the construction and building one, the promotion of circularity principles throughout the life-cycle of buildings is emphasised by considering measures to improve the durability and adaptability of built assets, thus reducing both pressure on natural resources and construction and demolition waste generation. The revision of the Construction Products Regulation (Regulation (EU) 305/2011) is also foreseen as one of the deliverables of the action plan in order to address the sustainability performance of construction products.

The holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to the importance of disaster prevention measures and integration of risk reduction and cohesion policies. Furthermore, the Acton Plan on the Sendai Framework for Disaster Risk Reduction 2015-2030 (Commission SWD 2016/205) promotes EU and national investments for disaster risk reduction and supports the development of a holistic disaster risk management by integrating the 'Build Back Better' objective to strengthen resilience of built environment.

Furthermore, integrated seismic and energy retrofit technologies help to preserve cultural heritage sites according to the European Framework for Action on Cultural Heritage (Commission SWD 2019), which emphasises the need to safeguard the EU built heritage against natural disasters and climate change.

Key conclusions

The study consists of three main parts: (i) a simplified analysis of the EU existing buildings most needing combined seismic and energy retrofit, along with a focus on the Italian context, (ii) a review and classification of seismic retrofit technologies, and (iii) a review and ranking of energy retrofit technologies.

In the context of the first part of the study, the following key conclusions are achieved:

- The majority of the EU existing building stock suffers from both structural deficiencies, mainly in seismic prone regions, and energy inefficiency. Hence, combined seismic and energy retrofit becomes an essential priority to achieve a safe, sustainable, and resilient built environment. However, the diversity of the EU buildings complicates a large-scale modernisation. Based on the analysis of main characteristics of the EU existing residential buildings in terms of age, size, and construction material and on the mapping of the EU territory in seismic and climatic zones, the EU buildings most needing combined retrofit need to be identified. This prioritisation helps to simplify the selection of effective retrofit technologies and speed up the EU building renovation.
- Italy represents a particular case study for the investigation of the EU buildings needing combined seismic and energy retrofit due to the huge variability of the Italian building stock in terms of construction technologies, structural details, and envelope components.

In the context of the second and third parts, the following key conclusions are carried out:

- Seismic retrofit technologies rely on two main intervention approaches: (i) global and (ii) local interventions, operating at level of structural system as a whole and individual structural elements, respectively. The qualitative classification of the investigated seismic retrofit technologies based on Life Cycle Thinking (LCT) criteria and the quantitative one aimed at carrying out average unit cost ranges of relevant interventions for both RC and masonry buildings represent a supporting tool to facilitate the decision making process of different stakeholders in the preliminary stage of a retrofit design.
- Energy retrofit technologies can be classified in active and passive interventions, depending on solutions concerning the energy system (i.e. heating, ventilation, and air conditioning systems) and the components of the building envelope, respectively. In the view of a combined/integrated seismic and energy renovation, passive solutions differentiated by wall, floor, roof, window, and door components are investigated. The qualitative assessment of their level of compatibility with the EU building typologies located in the EU countries exhibiting a high-to-moderate seismic hazard provides a useful tool to address their applicability. Furthermore, the qualitative ranking of selected energy retrofit technologies in terms of their attractiveness for potential investment to implement combined seismic and energy renovation provides a classification of the preferable options to ease the decision making process in the initial phases of a retrofit design.

Main findings

Main findings of the study concern both the investigation of the EU existing buildings most needing combined seismic and energy retrofit with a focus on the Italian context and the overview and classification of the seismic and energy retrofit technologies to provide a 'catalogue' of effective retrofit strategies in the preliminary phase of a renovation project.

A **simplified prioritisation of the EU existing buildings** most needing combined seismic and energy retrofit is essential to facilitate a wide renovation of the EU built environment. The analysis was carried out by means of a three-step approach. As for the first step, the EU residential building stock resulting into the most widespread construction segment in Europe was analysed. Nearly 80 % of EU dwellings were built before 1990 and more than 20 % before 1945, thus complying neither with the modern seismic design code requirements (e.g. Eurocodes), neither with the recent energy efficiency directives. Both single- (SFHs) and multi- (MFHs) family houses need to be considered in the modernisation of the EU residential building stock since more than 50 % of the EU dwellings are located in three- or more-dwelling buildings (i.e. MFHs), followed by 40 % of dwellings in one-dwelling buildings (i.e. SFHs). Focusing on their size, it was pointed out that the mean value of the EU average floor area per dwelling is equal to 100 m^2 and 68 m^2 for SFHs and MFHs, respectively. Finally, both reinforced concrete (RC) and masonry buildings result into the predominant constructions in the EU. As for the second step, the EU territory was subdivided in low, medium, and high seismic hazard zones based on specific peak ground acceleration (PGA) range values according to the European Seismic Hazard Model 2020. Similarly, the EU was mapped in six climatic zones based on the 2019 average annual data of heating degree days (HDD) per EU Member State.

As for the third step, based on the analyses carried out within the two previous steps, the EU Member States most needing combined seismic and energy retrofit were selected according to a prioritisation score-based approach relying on PGA, HDD, and cooling degree days (CDD) data per EU Member State. Specifically, Bulgaria, Croatia, Greece, Italy, and Romania were selected as countries exhibiting high-to-moderate seismic hazard and severe climatic conditions, along with Germany to also consider a western European country with low-to-moderate seismic hazard. Subsequently, ad-hoc analyses correlating residential building age, year of implementation of moderate seismic design codes and initial energy efficiency regulations, and building type in terms of construction material were carried out in the different examples of regions corresponding to the various possible combinations of seismic hazard and climatic conditions in each selected country. Main results point out a potential to apply combined upgrading to at least 60–70 % of the existing residential building stock in the selected EU priority countries. Furthermore, both masonry and RC buildings in all the selected priority countries need for a combined retrofit, prioritising stone and bricks masonry buildings, mainly in Bulgaria and Croatia, as well as RC wall and framed structures, mainly in Greece, and Romania.

Seismic retrofit technologies focus on global and local strengthening interventions. Global interventions common to different building typologies refer to retrofit solutions aimed at either reducing the seismic demand, such as seismic isolation and additional damping, or enhancing the seismic capacity of the existing structure by means of a new additional seismic-resistant structural system. The latter concerns different alternatives including RC infills, RC walls, rocking walls, steel bracing frame systems, and external exoskeleton solutions (i.e. shear wall exoskeleton and shell exoskeleton). Local interventions differ by building typology focusing on RC and masonry buildings. As for RC buildings, local interventions aim to improve strength and ductility of RC beams, columns and joints, whereas as for unreinforced masonry buildings, the main local interventions concern the improvement of masonry quality of load-bearing walls, along with the continuity of their layers, before proceeding with wall strengthening.

The qualitative assessment of the investigated seismic retrofit technologies based on LCT criteria, including different environmental, economic, social, and technical aspects throughout the entire life cycle of a building, points out that steel bracing frame systems and external shell exoskeleton solutions result particularly LCT-effective. Indeed, these technologies exhibit several LCT benefits, such as total compatibility with holistic renovation, minimum disruption of occupants, use of prefabricated elements easily demountable and recyclable/reusable. Furthermore, the shell exoskeleton solution based on the use of cross laminated timber (CLT) panels results into a very promising technology for a holistic renovation encompassing structural, energy, and architectural restyling.

The quantitative assessment of relevant seismic retrofit solutions for both RC and masonry buildings based on a detailed two-phase cost analysis enables to identify their average unit cost ranges, which become an useful supporting tool in the preliminary phase of the renovation design of an existing building to facilitate the stakeholders' initial decisional process. Indeed, this inventory can be used to develop budget estimates, enable project financing, pre-screen and compare retrofit strategies. Specifically, as for masonry building, new RC or steel-braced shear walls outside the building account for the highest average unit-cost range (510-880 €/m^2 or 530-910 €/m^2 of shear wall vertical surface, respectively) mainly due to the cost of the new foundation system. As for RC buildings, seismic isolation results into the highest average unit cost range, followed by the shear wall solution (i.e. the same as for masonry buildings). However, it is worth noting that results were carried out with reference to particular geometries and assumptions (i.e. construction site located in Italy, medium-size buildings, reasonable access to construction site), thus cost fluctuations can occur for different cases.

Energy retrofit technologies refer to energy efficiency technologies (EETs) operating at building envelope components. Solutions aimed at improving the thermal performance of walls, roofs and floors, windows and doors are investigated, encompassing both traditional technologies (e.g. thermal insulation solutions for wall, floor and roof, replacement and weather-stripping interventions to reduce air infiltration of windows and doors), and modern technologies (e.g. green façades, and green or cool roofs), which also provide benefits in global warming reduction.

The ranking of selected energy retrofit technologies based on their attractiveness for potential investments to implement integrated seismic and energy renovation of residential buildings in the EU countries exhibiting high-to-moderate seismic hazard has been carried out. Insulation of external wall air chambers, internal insulation of roofs, and internal insulation of external walls result into highly attractive EETs for potential investments. These results depend on low cost, high cost effectivity, and low waste generated of these energy renovation technologies, although the applicability of the insulation of external wall air chambers is compatible with a low share of buildings. Replacement of doors/windows and prefabricated units for external wall insulation or external thermal insulation composite systems reveal medium and low rank of attractiveness, respectively.

Related and future JRC work

JRC activities related to the pilot project REEBUILD with regards to the analysis of technologies for combined upgrading of existing buildings refer to previous and on-going work within the **iRESIST+** ([3]) project devoted to explore innovative integrated seismic and energy retrofitting solutions for existing buildings (Bournas, 2018, Pohoryles et al., 2020, Pohoryles and Bournas, 2021).

JRC activities on approaches for assessing the combined effect of upgrading complementary to the pilot project REEBUILD refer to previous work carried out within the SAFEty and SUSTainability (**SAFESUST**) project, aimed at defining a holistic approach to optimise at the same time safety and sustainability of built environment (Caverzan et al., 2018). One the most significant contributions of SAFESUST concerns the development of the Sustainable Structural Design (SSD) methodology (Lamperti Tornaghi et al., 2018), which includes the energy and environmental performances into the structural one by combining the results into a global assessment parameter in monetary units. The SSD methodology has been considered as point of reference for the development of a simplified combined assessment method introduced within REEBUILD project.

In the perspective of a broader vision of a sustainable, beautiful and inclusive built environment in line with the three dimensions of the New European Bauhaus initiative, JRC has recently initiated to conduct a **Preparatory Action 'NEB Knowledge Management Platform'** in the context of the NEB Lab project on a labelling strategy ([4]) to develop a self-assessment tool allowing interested parties to align with the three NEB dimensions (i.e. sustainable, beautiful, and together values), while designing, implementing or assessing NEB transformation projects (e.g. buildings, living spaces). This on-going activity results complementary to REEBUILD project since it expands the combined seismic and energy assessment of buildings to a multitude of aspects related to environment, economy, functionality, beauty, context, etc. to assess the overall performance of a project in a holistic way.

Quick guide

This report aims to provide a simplified analysis of the EU building typologies most needing combined seismic and energy retrofit, as preliminary step for an overview of the most common seismic and energy retrofit technologies. **Section 1** focuses on a general introduction on the need of an integrated seismic and energy retrofit of existing buildings. **Section 2** provides a simplified prioritisation of the EU buildings most needing combined retrofit, along with a focus on the Italian context due to the huge variability of its existing building stock. **Section 3** is devoted to a brief synopsis of seismic retrofit technologies, which are subsequently classified both qualitatively in terms of LCT-based criteria, and quantitatively through a cost analysis to provide average unit cost ranges of the most common retrofit technologies for masonry and RC buildings. Similarly, **Section 4** focuses on a brief review of energy retrofit technologies operating at building envelope component level, to be classified qualitatively by means of a set of indicators to subsequently rank selected technologies by means of a multi-criteria decision-making analysis. Final remarks and conclusions of the study are summarised in **Section 5.**

([3]) iRESIST+ project, https://joint-research-centre.ec.europa.eu/iresist-home_en

([4]) NEB Lab: Labelling Strategy, https://new-european-bauhaus.europa.eu/get-inspired/inspiring-projects-and-ideas/neb-lab-labelling-strategy_end

1 Introduction

The European building stock, considering both residential and non-residential segments, accounts for 25 billion square meters of built-up area (BPIE, 2011), of which 20 billion erected before 1990, thus representing ageing built environment compliant neither with the recent energy efficiency regulations, nor with modern seismic design code requirements.

The achievement of an energy-efficient built environment by boosting renovation solutions for obsolete buildings is a high-priority issue for Europe. Indeed, a large-scale renovation of buildings represents not only an effective key to meet the EU ambitious energy and climate targets in line with the European Green Deal priority (COM(2019) 640), but it can also generate economic and social benefits, fulfilling the sustainable development principles. Nevertheless, the annual energy renovation rate of the EU building stock is still very low, being equal to only 1 %. Thus, the European Commission has emphasised the need for a large-scale upgrading of the EU existing building stock in line with the Renovation Wave strategy (COM(2020) 662), in order to ensure that the building sector effectively plays its fundamental role in both reducing GHG emissions by at least 55 % below 1990 levels by 2030 and achieving the overarching goal of climate-neutrality by 2050, set off by the first European Climate Law (EU 2021/1119). Moreover, the 2022 Russian-Ukraine war has made the challenge of a deep renovation of the EU existing buildings stock even more urgent, calling for increased energy efficiency and savings for an accelerated transition towards renewable energy sources, as at the heart of the REPowerEU plan (COM(2022) 230. However, any action aimed at achieving exclusively the optimisation of the energy performance of existing buildings without simultaneously addressing structural safety could be a business dead-end, mainly in seismic prone regions. Indeed, seismic events may yield huge economic and social losses, along with detrimental environmental impacts, also leading to a high likelihood of the loss of the energy retrofit intervention, if any (Marini et al., 2014, Margani et al., 2020). Moreover, natural hazards and climate change also play a detrimental impact on safety of buildings, causing economic, social, and environmental burdens, if buildings do not comply with structural design standards towards resilience-based design and renovation (Athanasopoulou et al., 2020, Sousa et al., 2020, European Commission, 2023)

The promotion of an integrated renovation approach reveals crucial to achieve a safe, sustainable and resilient built environment, as also underlined by the 2030 Agenda for Sustainable Development. The effectiveness of an integrated retrofit intervention compared to a traditional uncoupled seismic or energy retrofit solution emerges when broadening the time frame of the analysis, shifting from the construction time to a life-cycle perspective, also accounting for the building operation phase, as well as for the end-of-life management (Menna et al., 2013, Wei et al., 2016, Marini et al., 2017, Passoni et al., 2021). In this case the potential of a holistic approach becomes clear in maximising benefits and performances, while reducing costs, impacts on the inhabitants and burdens on the environment over the building life cycle.

In the above context, the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD was launched to put forward a simplified holistic approach to enhance simultaneously the seismic safety and energy efficiency of the existing European building stock and to stimulate the use of integrated solutions in a life-cycle perspective. A preliminary crucial step to carry out an effective large-scale integrated renovation of the EU existing building stock deals with the identification of building typologies most needing combined seismic and energy retrofit. Indeed, buildings in Europe vary remarkably in terms of their function, typology, and main architectural, and technological features. Accordingly, the retrofit needs of existing buildings can be very different depending on the age of construction, the location, the structural typology and the material characteristics (Marini et al., 2014). This investigation facilitates the selection of technology options for an effective combined seismic and energy retrofit intervention. To this end, the analysis of seismic and energy retrofit technologies is fundamental to provide stakeholders with an overview of the main advantages and disadvantages of retrofit technologies. The assessment of the applicability of these technologies, mainly in terms of compatibility, cost, and disruption time, is also crucial to facilitate the decision making process in the preliminary stage of renovation projects to achieve a large-scale modernisation of the existing built environment by overcoming economic, technical, and administrative renovation barriers (La Greca, and Margani, 2018).

This report aims to provide a simplified analysis of the EU building typologies most needing combined seismic and energy retrofit, as basis for an overview of the most common seismic and energy retrofit technologies. Following this introduction, **Section 2** provides a simplified prioritisation of the EU buildings most needing combined retrofit, after analysing its main characteristics in terms of age, size, construction material and mapping the EU in seismic hazard and climatic zones**.** A focus on the Italian existing residential building stock is also carried out, due to its huge variability in terms of construction technologies. The evolution of seismic design code and seismic zonation, as well as of the energy efficiency regulations in Italy is first summarised to provide general remarks on seismic vulnerability and energy inefficiency of Italian existing buildings. Subsequently, the Italian masonry and RC residential building typologies most needing combined retrofit are presented. **Section 3** provides a brief review of seismic retrofit technologies focusing on interventions involving the structural system as a whole (global level) and individual structural elements (local level). Relevant technologies are classified both qualitatively by means of LCT-based criteria and quantitatively through a cost-analysis of actual seismic retrofit projects of existing masonry and RC buildings in Italy to carry out average cost-ranges of the most common seismic retrofit interventions, useful in the preliminary stage of a building renovation design. **Section 4** focuses on the review of energy retrofit technologies operating at level of building envelope components, along with an analysis of their compatibility with the EU building typologies**.** Selected energy retrofit technologies are qualitatively classified and ranked based on their attractiveness for potential investments to implement integrated seismic and energy renovation of existing buildings. Finally, **Section 5** summarises the final remarks and conclusions of the study. It is worth noting this report aims to expose the study in a simplified way, mainly useful for policymakers, whereas a comprehensive presentation of some outcomes above including both technical and computational details can be found in the related JRC technical reports (Romano et al., 2023).

2 EU buildings needing combined seismic and energy retrofit

The huge number and diversity of the EU buildings typically make the possibility of a rapid renovation for a large fraction of existing buildings complex. A simplified analysis for the identification of EU buildings simultaneously needing seismic strengthening and energy efficiency improvement is first presented (Section 2.1), along with a focus on the Italian context (Section 2.2). The reader is recommended to refer to the related JRC technical report (Romano et al., 2023) for an in-depth overview of both investigations, also including technical and computational details.

2.1 Investigation on EU building typologies needing combined retrofit

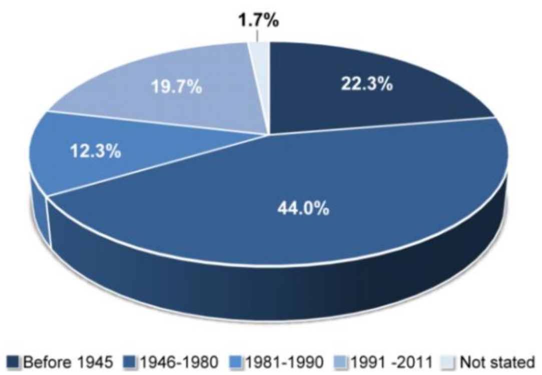
A simplified prioritisation of the EU buildings most needing combined seismic and energy retrofit was carried out according to a three-step approach. First, the main characteristics of the EU existing building stock are investigated. Second, the EU territory is mapped in seismic hazard zones and climatic zones. Third, based on these results, a simplified two-step analysis for the identification of the EU residential buildings most requiring seismic strengthening and improvement of energy efficiency is presented by concentrating on selected EU Member States, characterised by severe seismic-climatic scenarios. Each of the three steps above is briefly presented in the following.

2.1.1 Main characteristics of the EU existing residential building stock

The residential building stock, consisting of single- (SFHs) and multi-family houses (MFHs), represents the most widespread construction segment in Europe. Its main characteristics in terms of age, building type (namely. one-dwelling, i.e. SFHs, two-dwelling, and three- or more-dwelling, i.e. MFHs, buildings), size, and construction material are analysed, as it follows:

- **Age** - The distribution of dwellings by year of construction in Europe (i.e. EU-27, Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) during the period pre-1919 - 2011 is investigated according to data retrieved by the 2011 Population and Housing Census of the European Statistical System (ESS). Results (Figure 1) indicate that the highest share of European dwellings in both residential and non-residential buildings was built between 1946 and 1980, accounting for a percentage equal to 44 % of the entire number of dwellings. More than 20 % and nearly 79 % of the European dwellings were built before 1945 and 1990, respectively. Hence, the majority of the European existing dwellings do not comply with both the recent EU energy efficiency provisions and modern seismic design code requirements (e.g. Eurocodes).

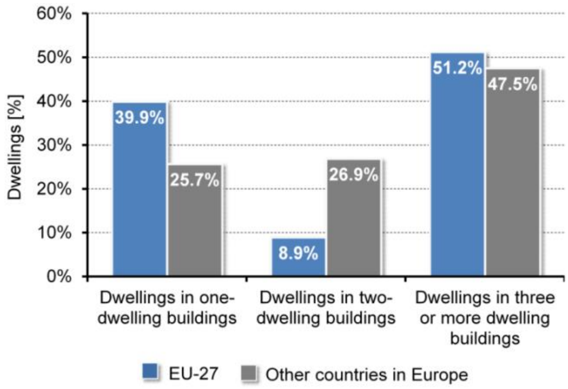
Figure 1. Percentage distribution of dwellings in residential and non-residential buildings in Europe by year of construction (pre-1919-2011), grouped into four construction periods



Source: Data - ESS, EU Population and Housing Census (2011).

- **Building type** - The analysis of the distribution of dwellings in residential and non-residential buildings in Europe (i.e. EU-27, Iceland, Liechtenstein, Norway, Switzerland, and United Kingdom) is carried out along with a focus on the distribution of dwellings in residential buildings by building type, according to data retrieved by the ESS 2011 Population and Housing Census. Nearly the total segment of dwellings in Europe is located in residential buildings, accounting for 98.5 % in the EU-27, with the highest share (i.e. more than 50 %) of dwellings located in three- or more-dwelling buildings, followed by 40 % of dwellings in one-dwelling buildings. Only 9 % of the EU dwellings is located in two-dwelling buildings (Figure 2). Hence, both SFHs and MFHs need to be considered in the modernisation of the EU building stock. Estonia, Latvia, Spain, Italy are the EU countries exhibiting the highest number of dwellings in MFHs, whereas Ireland accounts for the highest share of dwellings in SFHs, followed by Belgium and the Netherlands with significant fractions.

Figure 2. Dwellings in residential buildings by building type in Europe



Source: Romano et al. (2023), Data - ESS, EU Population and Housing Census (2011)

- **Size** - The distribution of number of dwellings by size, expressed as useful floor area per dwelling, in the majority of the EU Member States is analysed according to statistical data retrieved by the ESS 2011 Population and Housing Census. The highest share of dwellings in the investigated EU Member States (data are not available for all the EU-27) accounts for a useful floor area resulting into the range 50-120 m^2. Furthermore, the investigation on the average floor area of SFHs and MFHs in the EU-27 (except Croatia and Cyprus – data are not available) is carried out according to the 2008 data retrieved by the dedicated tool developed within the 'Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe (ENTRANZE)' project ([5]). Results point out that generally SFHs accounts for higher average floor area than MFHs in the majority of the investigated EU Member States. The mean value of the EU average floor area per dwelling is equal to 100 m^2 and 68 m^2 for SFHs and MFHs, respectively.
- **Construction material** – The EU distribution of the number of dwellings/residential buildings by main construction material is analysed, according to data retrieved by NERA project ([6]) (Ozcebe et al., 2014), as national statistical institutes providing these data are limited to few EU Member States. General indications on the distribution of the EU buildings by construction materials point out that the majority of the EU building stock consists of masonry buildings, followed by RC constructions. However, some countries, such as Portugal, and Greece, account for higher fractions of RC buildings. Furthermore, low but no negligible shares of timber buildings are concentrated in few Member States, such as Sweden, Finland, Germany, and Romania.

2.1.2 Mapping the EU in seismic and climatic zones

The seismic hazard of a territory is represented by the frequency and the intensity of potential earthquakes occurring in that specific area. Thus, seismic hazard can be defined as the probability of a potential earthquake occurring in a specific geographical area with a ground shaking intensity, expressed as an expected PGA with an expected probability to be exceeded in an assumed time period. Focusing on Europe, low, moderate, and high seismic hazard zones can be identified depending on specific PGA ranges

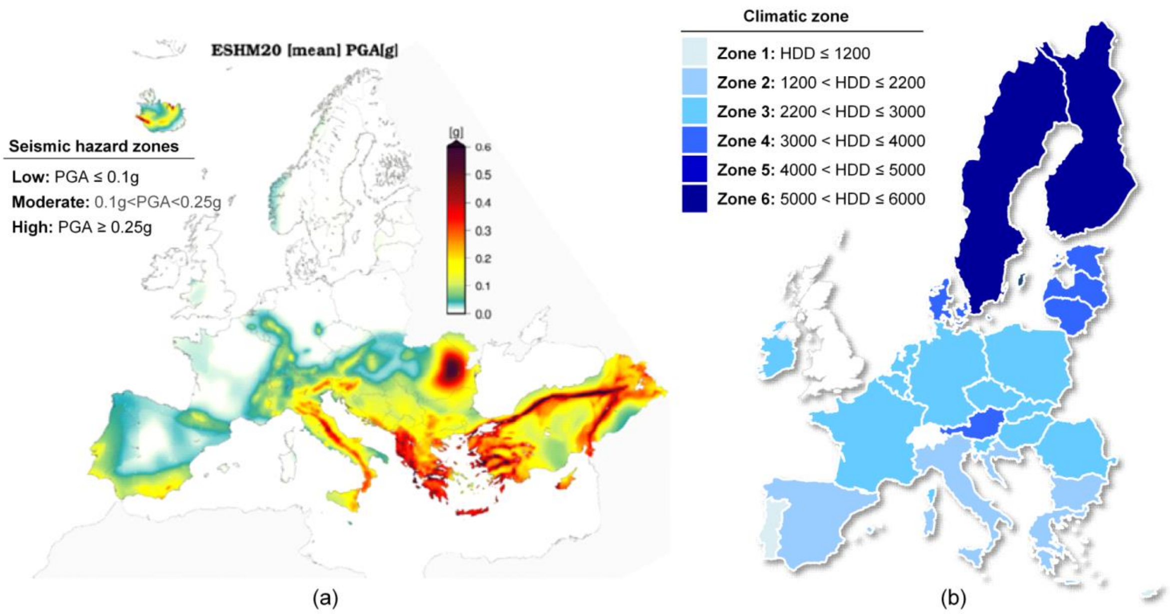
([5]) The 2012-2014 'Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe' (ENTRANZE) project (https://www.entranze.eu/) supports policy making by providing the required data, analysis and guidelines to achieve a fast and strong penetration of nearly Zero Energy Buildings (nZEB) within the existing national building stocks. Its dedicated tool, named *ENTRANZE tool* (https://www.entranze.eu/tools/interactive-data-tool), contains an in-depth description of the characteristics of buildings and related energy systems in the former EU-28 and Serbia.

([6]) The 2010-2014 'Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation' (NERA) project (https://cordis.europa.eu/project/id/262330) has led to a series of deliverables (https://www.orfeus-eu.org/other/projects/nera/) to achieve an improvement and a long-term impact in the assessment and reduction of the vulnerability of constructions and citizens to earthquakes.

corresponding to PGA ≤ 0.1g, 0.1g < PGA < 0.25g, and PGA ≥ 0.25g, respectively, with the 10 % exceedance probability in 50 years, according to the 2020 European seismic hazard map based on the 2020 update of the European Seismic Hazard Model (ESHM20) (Danciu et al., 2021) (Figure 3a). Turkey, Greece, Albania, Italy, and Romania represent the countries with the highest seismic hazard in Europe, followed by the other Balkan countries. However, high seismic hazard can be also observed in some regions of Austria, France, Germany, Iceland, Portugal, and Spain, among others.

Energy uses affected by climate conditions are mainly space heating and space cooling, thus the HDD and CDD parameters become valid tools to identify the EU climatic zones. HDD and CDD are weather-based technical indexes derived from outside air temperature measurements on a daily basis and used to estimate the heating and cooling energy demands of buildings, respectively. The HDD and CDD calculated on daily basis are subsequently aggregated to provide monthly and annual data, available in Eurostat at the EU-27 level, as well as at different regional level within each country according to the Nomenclature of Territorial Units for Statistics (NUTS) classification, i.e. NUTS-2 (basic regions), and NUTS-3 (small regions) levels. Based on the EU 2019 HDD average annual statistics at Member State level (Eurostat, 2020), six climate zones have been identified as a function of specific HDD ranges (Figure 3b), as also defined in Pohoryles et al. (2020): (i) Zone 1 (HDD ≤1200), (ii) Zone 2 (1200<HDD≤2200), (iii) Zone 3 (2200<HDD≤3000), (iv) Zone 4 (3000<HDD≤ 4000), (v) Zone 5 (3000<HDD≤ 4000), and (vi) Zone 6 (5000<HDD≤ 6000).

Figure 3. (a) European seismic hazard map for ESHM20, (b) EU-27 climatic map based on 2019 HDD average annual values according to six climatic zones



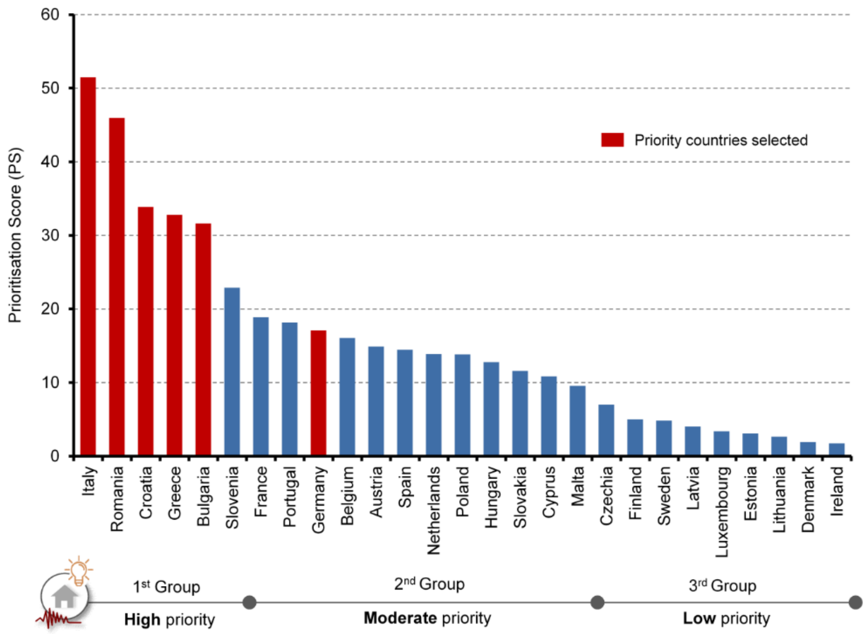
Source: (a) ©Danciu et al. (2021), (b) Data – Eurostat (2020)

2.1.3 Simplified prioritisation of EU buildings needing combined retrofit

A simplified analysis on the prioritisation of the EU residential buildings requiring a combined seismic and energy retrofit is carried out according to a two-step framework, based on results carried out within the previous steps and briefly summarised, as follows:

— **Step 1: Priority EU Member States for a combined retrofit of buildings** - The EU Member States most needing combined seismic and energy retrofit of buildings are identified. A simplified investigation is carried out according to a score-based approach dealing with the computation of a prioritisation score (PS) based on the maximum reference PGA value, and the 2019 HDD and CDD highest average annual values at NUTS-3 region level for each EU Member State. The distribution of the EU-27 by the corresponding PS, ranging from the highest to the lowest result, is depicted in Figure 4. Based on each PS per Member Sate, the EU-27 can be aggregated into three main groups, depending on the level of priority: high, moderate, and low priority countries. Bulgaria, Croatia, Greece, Italy, and Romania are selected within the first group as high priority countries characterised by moderate-to-high seismic hazard and significant climatic conditions. Germany is also selected within the second group as a moderate priority country in order to provide a more detailed and comprehensive analysis by including a western European country with low-to-moderate seismic hazard. Furthermore, Germany is found to be the EU country with the highest number of dwellings in both residential and non-residential buildings (i.e. more than 40 million), according to data retrieved by the ESS 2011 Population and Housing Census.

Figure 4. EU-27 distribution by prioritisation score based on the combination of seismic hazard and climatic conditions



Source: Romano et al. (2023)

— **Step 2: Simplified prioritisation of potential residential buildings needing combined retrofit in the selected EU priority Member States** – The EU priority countries (selected in Step 1) are further investigated at NUTS-3 level to identify examples of potential regions corresponding to the various possible combinations of seismic hazard and climatic conditions in each country by means of a seismic-climatic matrix (Table 1) based on the three seismic hazard zones and five out of the six climatic zones, according to the 2020 ESHM map and the EU climate map in terms of 2019 HDD average annual values, respectively.

Subsequently, ad-hoc analyses correlating residential building age, year of implementation of moderate seismic design code and first energy efficiency regulations, and building type in terms of construction material were carried out in the different examples of regions within the selected countries. The distribution of the number of residential buildings or dwellings (depending on data availability) by year of construction in all the NUTS-3 regions selected within each EU priority country (see Table 1) was analysed, according to data provided by the 2011 Census of the corresponding national statistical institutes or the ESS, and correlated with the year of implementation of both seismic design code and energy efficiency regulations. Specifically, as for the seismic design code, the year corresponding to the introduction of the moderate seismic design code is considered for each EU priority country, according to Crowley et al. (2021). As for energy efficiency regulations, generally the 1970s is recognised as the decade when the first thermal regulations of buildings were introduced to respond to the worldwide energy crisis in 1973, although they were often neglected. Hence, a general assumption indicating 1980 as the year of implementation of more stringent energy efficiency provisions (Bournas, 2018) was considered for all the EU priority countries.

Main results point out a potential to apply combined upgrading to at least 60–70 % of the existing residential building stock in the regions of the selected EU priority countries, mainly referring to scenarios characterised by high-to-moderate seismic hazard and severe climatic conditions. However, attention needs to be also drawn to the buildings located in low-to-moderate seismic hazard regions. Furthermore, both masonry and RC buildings in all the regions of the selected priority countries needs a combined retrofit, prioritising stone and bricks masonry buildings, mainly in Bulgaria and Croatia, as well as RC wall and framed structures, mainly in Greece, and Romania.

Table 1. Seismic-climatic matrix for the selected EU priority countries

CLIMATIC ZONE (HDD)	**SEISMIC HAZARD ZONE** Low (PGA ≤ 0.1g)	Moderate (0.1g < PGA < 0.25g)	High (PGA ≥ 0.25g)	**EU Country**
Zone 1 (HDD ≤ 1200)		Andros	Athens	GR
	Trapani	Napoli	Reggio Calabria	IT
Zone 2 (1200 ≤ HDD<2200)		Pleven	Plovdiv	BG
		Split	Dubrovnik	HR
		Kozani	Preveza	GR
	Bari	Pisa	Cosenza	IT
		Bucharest		RO
Zone 3 (2200 ≤ HDD<3000)		Sofia	Blagoevgrad	BG
	Osijek	Primorje-Gorski kotar	Zagreb	HR
		Kastoria		GR
	Munich	Aachen		DE
	Como	Vicenza	L'Aquila	IT
	Cluj	Satu Mare	Vrancea	RO
Zone 4 (3000 ≤ HDD<4000)	Lindau			DE
	Trento	Belluno		IT
	Bistrita	Hargita	Covasna	RO
Zone 5 (4000 ≤ HDD<5000)	Aosta			IT

Source: Romano et al. (2023)

2.2 Focus on Italian building typologies needing combined seismic and energy retrofit

Italy results into one of the EU-27 high priority countries, where combined seismic and energy retrofit of its existing building stock is deeply needed. Furthermore, Italy represents a particular case-study due a huge variability of its buildings in terms of construction technologies, structural details, and envelope components. This heterogeneity typically depends on local raw material supply, workmanship, evolution of seismic design codes and energy efficiency regulations over time. Hence, an analysis of the Italian building typologies most needing combined seismic and energy retrofit is carried out. The evolution of both seismic design code and energy efficiency regulations in Italy is briefly summarised in the following paragraphs, as a preliminary step in the perspective of the simplified prioritisation of the Italian building typologies. This overview may provide a general indicative figure of the seismic vulnerability and energy performance of the existing residential building stock by comparing the time periods when significant legislation developments were issued with the periods of construction of buildings. Based on this synthesis, a research focus investigating the Italian masonry and RC residential building typologies needing combined seismic and energy retrofit is presented.

2.2.1 Evolution of seismic design code and energy efficiency regulations in Italy

2.2.1.1 Evolution of Italian seismic design code and seismic zonation of the Italian territory

The evolution of the Italian seismic design code, since its roots at the end of the 18th century, has reflected the occurrence of severe seismic events (Boschi et al., 2000), leading to direct and indirect losses mainly in terms of extensively damaged/collapsed buildings and fatalities. The catastrophic consequences of these natural disasters over time have provided the corresponding impulses for the introduction of the first generation of seismic design code in 1909, after the 1908 Reggio Calabria and Messina earthquake, until the adoption of the modern seismic design code, as arose in the last two decades in the aftermath of both the 2002 Molise and the 2009 L'Aquila earthquakes.

The temporal evolution of the Italian seismic design code can be summarised into four main phases: (i) Phase I - pre-code phase, (ii) Phase II - first generation of seismic design code, (iii) Phase III - second generation of seismic design code, (iv) Phase IV – the latest generation of seismic design code. Each phase corresponds to different categories of seismic design, based on the classification provided in Crowley at al. (2021) and adapted to the Italian context: (i) Phase I: no code (pre-1909), (ii) Phase II: low code (1909-1995), (iii) Phase III: moderate code (1996 – 2002), and (iv) Phase IV: high code (2003 – to date). Each phase is briefly summarised, as it follows:

- **Phase I** - The phase I represents a pre-code phase during which practical seismic design rules for safe constructions were introduced, setting a remarkable qualitative step towards quantitative studies for the future development of the first generation of Italian seismic design code in the 20th century (Marotta et al., 2019). Significant insights related to the pre-code phase were achieved after the 1783 sequence of earthquakes in the South Calabria area leading to the introduction of the first Italian 'seismic design rules' (Vivenzio, 1788), which included a primordial earthquake-resistant construction, named 'Baraccata' building system (Ruggieri, 2017). Further set of practical 'seismic design rules' on maximum heights of buildings, construction criteria, qualitative understanding of the role of site response were proposed after the 1859 Norcia earthquake (Central Italy) and 1883 Ischia earthquake (Southern Italy), as reviewed in Marotta et al. (2019).
- **Phase II and III** – The phase II initiated with the introduction of the first seismic design code in 1909 and its following evolution of low seismic design code until the adoption of the moderate seismic design code in 1996 (Ministerial Decree 16/01/1996), which marked the beginning of the Phase III. Following the decree issued in 1909, the development of the Italian low seismic design code in the first decades of the 20th century was essentially devoted to masonry buildings, since this building typology represented the most widespread construction segment at that time, with a fundamental step provided in 1915 (Royal Decree 573/1915), which explicitly introduced the first provision regarding the value of the horizontal seismic base shear. The first structural design code focused on RC buildings dates back to 1939 (Royal Decree 2229/1939), although no seismic design provisions were defined. The first few provisions in terms of seismic design for all buildings (i.e. RC, steel and masonry buildings) were introduced at the beginning of 1960s (Law 1684/1962). An important change in the Italian structural design code for buildings in seismic areas was enforced in 1975 (Ministerial Decree 3/03/1975), through the introduction of the response spectrum in seismic design. However, focusing on masonry buildings, the 1975 decree only recalled the construction design provisions regarding building height limits and construction details, which were introduced in the law 1684/1962. Indeed, the first comprehensive structural design code for masonry buildings was issued only in 1987 (Ministerial Decree 20/11/1987). The 1975 was followed by a series of different legislative acts following catastrophic seismic events (e.g. the 1976 Friuli and 1980 Irpinia-Basilicata earthquakes), which introduced mandatory seismic safety checks for existing buildings (e.g. Ministerial Decree 02/07/1981), and a few ministerial decrees during 1984-1987 as periodic updates of the existing structural design code for buildings in seismic areas up to the 1996 update with the release of the moderate seismic design code (Ministerial Decree 16/01/1996).
- **Phase IV** – The phase IV indicates the era of the high seismic design code started after the 2002 Molise earthquake with the adoption of the Ordinance of the Prime Minister (OPCM) 3274/2003, which introduced the limit states method for the design and retrofit of buildings in line with the Eurocode 8 (CEN, 2004). It was followed by the 'Italian Technical Standards for Constructions' in 2008 (NTC

2008)(Ministerial Decree 14/01/2008), which enforced the performance-based design approach with the introduction of specific limit states devoted to operation, damage limitation, life safety, and collapse prevention of structures. Furthermore, capacity design and local ductility criteria were prescribed. The standard NTC 2008 entered in force after the 2009 L'Aquila earthquake (Abruzzo region) and it was last updated in 2018 (NTC 2018) (Ministerial Decree 17/01/2018).

The evolution of the seismic zonation of the Italian territory reflects the development of specific legislative steps related to the evolution of the Italian seismic design code, as well as the occurrence of severe earthquakes. The first seismic zonation led to the classification of more than 450 Italian municipalities as seismic in Calabria and Sicily regions according to the Royal Decree 193/1909, following the 1908 Reggio Calabria and Messina earthquake. In the two following decades a series of legislative acts were issued to update the list of municipalities. Significant developments were achieved both in 1915 (Royal Decree 573/1915) with the addition of municipalities indicated as seismic in Lazio and Abruzzo regions, and in 1927 (Royal Decree 431/1927) when two seismic zones, named Category I (high seismicity) and Category II (moderate seismicity), were introduced. No considerable advancements, except from the de-classification of municipalities from seismic to non-seismic areas, were carried out until 1962 (Law 1684/1962), when it was underlined that seismic design codes should have been considered not only for municipalities hit by earthquakes. However, this prescription remained substantially void until the 1980s (Petruzzelli and Iervolino, 2021) with the release of two ministerial decrees following the 1980 Irpinia-Basilicata earthquake (Ministerial Decree 03/06/1981). A third seismic zone, named Category III, was introduced and for the first time the seismic zonation involved additional geographical areas not recently affected by an earthquake. The 2002 Molise earthquake, which hit a geographical area not classified as seismic at that time, provided the major impulse related to the seismic zonation of Italian territory by issuing the OPCM 3274/2003, which introduced a seismic zonation based on probabilistic values of the expected PGA. The introduction of the modern seismic design code significantly modified the role of the seismic zonation for structural design purposes. According to the NTC 2008 (Ministerial Decree 14/01/2008), design values of seismic actions refer to seismic hazard, expressed as local PGA values depending on geographical coordinates of the project area instead of seismic zones.

This synopsis highlights that Italian existing masonry and RC buildings may suffer from seismic vulnerability, since they do not comply with the modern seismic requirements provided in the NTC 2008 and in its 2018 updated version. Indeed, both standards have a little influence on seismic performance of existing residential masonry and RC buildings since a very minor extent of these new constructions have been erected after their entry in force. Furthermore, only 25 % of the Italian territory was classified as seismic until 1980.

2.2.1.2 Evolution of the Italian legislation on energy efficiency of buildings

The evolution of the Italian legislation on energy efficiency of buildings can be subdivided into two main eras, with the subdivision reference time marked by the introduction of the EU Energy Performance of Buildings Directive (EPBD) (Directive 2002/91/EC) in 2002, although the first EU legislative step related to energy efficiency in the construction sector dates back to the beginning of 1990s with the adoption of the directive 1993/76/EEC, also known as SAVE Directive (Council Directive 93/76/EEC). The pre-2002 era refers to the first generation of the national legislation on energy efficiency adopted into the period 1970-2001, whereas the post-2002 era includes the second generation of national regulations on energy efficiency to implement the EU EPBD requirements, according to their evolution over time. The main Italian legislative developments of both eras are depicted in Figure 5 and briefly summarised, as follows:

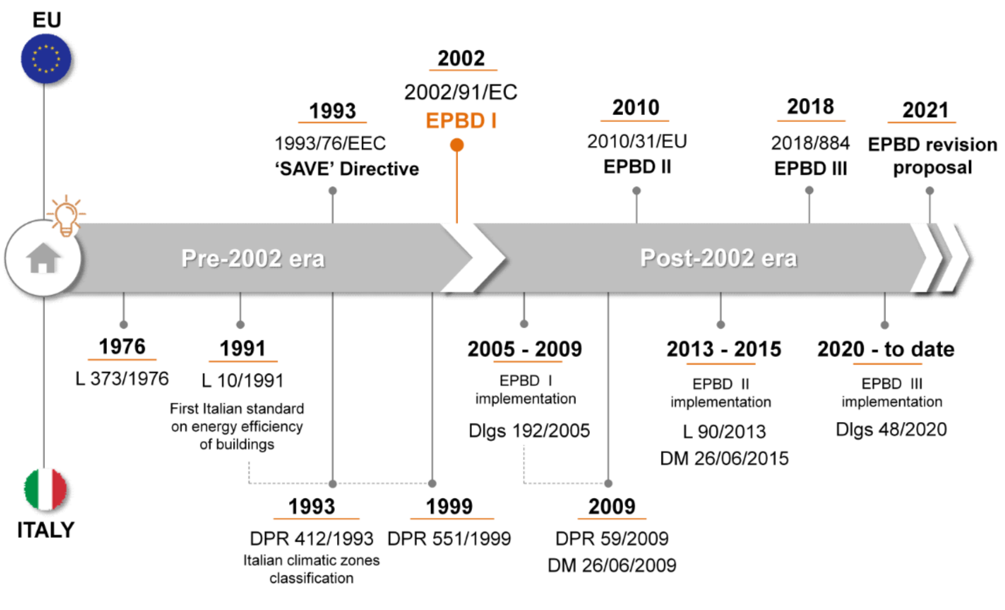
— **Pre-2002 era** - The Italian legislation on energy efficiency of buildings dates back to 1970s (Law 373/1976) to respond to the 1973 worldwide energy crisis. This law, aimed to reduce the energy consumption of buildings by addressing thermal insulation criteria in building design, was repealed in 1991, when the Law 10/1991 was issued to implement the National Energy Plan for the energy use, energy saving, and renewable energy use. The latter law is recognised as the first energy efficiency standard in Italy, introducing requirements for the reduction of the energy consumption of buildings along with new thermal criteria for the design and management of building envelope/energy consumption systems. Its implementation was addressed by two following Decrees of the President of the Italian Republic (DPR), (i.e. DPR 412/1993 and DPR 551/1999), regulating the calculation method of the annual energy demand for space heating of a building based on the HDD parameter and the volume of the building. It is worth noting that the DPR 412/1993 introduced the classification of the Italian territory in six climatic zones, as a function of HDD.

— **Post-2002 era** – The post-2002 Italian legislation on energy efficiency of buildings reflects the national implementation of the EU EPBD, from its first adoption (Directive 2002/91/EC), via its recast (Directive 2010/31/EU), to its revision (Directive 2018/844) – hereinafter, indicated as EPBD I, EPBD II, and EPBD III, respectively - leading to the three following main evolution phases:

  - **EPBD I implementation (2005 - 2009)** - The Legislative Decree (DLgs) 192/2005, amended by the DLgs 311/2006, set the basis for the EPBD I implementation in Italy. The two decrees were followed by a series of complementary legislative acts in 2009. These legislative acts refer to the DPR 59/2009 updating the calculation method and the minimum energy requirements, and the Ministerial Decree 26/06/2009 providing the national guidelines to carry out the compulsory energy performance certificate of buildings by an independent assessor, according to eight energy performance classes (i.e. from A+ to G, corresponding to a decreasing level of the energy efficiency of a building).
  - **EPBD II implementation (2013 - 2015)** - The Law 90/2013 implemented the EPBD II at national level by providing significant changes compared to the 2005, such as setting new criteria and energy performance requirements of buildings with energy demand needs to also be covered by renewable energy source. The EPBD II implementation at Italian level was completed with the adoption of the Ministerial Decree 26/06/2015, consisting of three inter-ministerial decrees focused on (i) minimum energy performance requirements of buildings (Ministerial Decree 26/06/2015 (15A05198)), (ii) technical report on building project attesting the minimum energy performance requirements (Ministerial Decree 26/06/2015 (15A05199)), and (iii) Energy Performance Certificate guidelines (Ministerial Decree 26/06/2015 (15A05200)).
  - **EPBD III implementation (2018 - to date)** - The Legislative Decree 48/2020 transposed the EU EPBD III at national level, with the main objectives to foster the energy upgrading of existing buildings and integrate the long-term renovation strategies to mobilise fiscal resources for the construction of nZEB buildings by 2050.

This synopsis underlines that the Italian legislation on energy efficiency of buildings is quite recent with stringent requirements adopted only in the last three decades.

Figure 5. Evolution of the Italian legislation on energy efficiency of buildings



Abbreviations and references to the legislation in the figure can be found in the *'List of abbreviations and definitions'* and *'References'* sections, respectively.

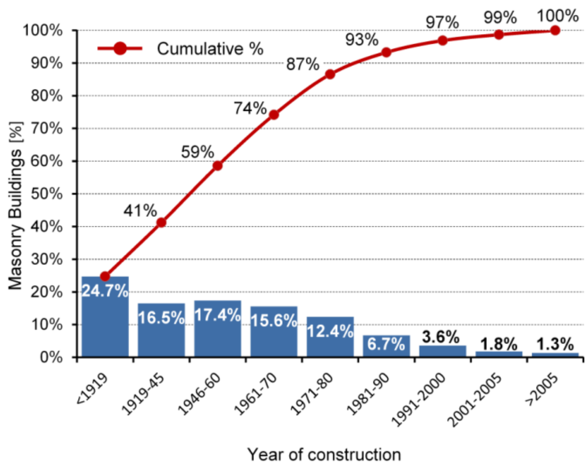
2.2.2 Italian masonry buildings needing seismic and energy retrofit

The analysis for a simplified prioritisation of Italian masonry building typologies is based on a three-step procedure, as it follows:

1. **Analysis of statistics on Italian masonry residential building stock –** Data on the age of Italian masonry residential building stock and its geographical distribution are analysed according to the 2011 Census of the Italian Statistical Institute (Istat, 2011).

   The distribution of masonry residential buildings by year of construction (Figure 6) shows that the oldest buildings date back to 1919 and early decades, accounting for the highest number of masonry buildings equal to 1.7 million (i.e. 24.7 %). Indeed, they become widespread in Italy in the past centuries due to the availability of natural blocks (e.g. rocks) in several regions substituted by artificial blocks (e.g. clay bricks) in locations where the raw material supply was absent. Hence, the use of masonry as main construction material was undisputed in Italy until the 2nd World War, when the requirement of rapid constructions with less architectural restraints arose to meet the need of housing a large extent of people in short time. RC buildings initiated to gain a great consensus to effectively achieve this goal. Regardless the growing popularity of RC buildings, the construction rate of masonry residential buildings continued to increase, nearly constantly, with an average extent equal to about 1 million of new constructions per decade until 1980. However, the following decades were characterised by the decline of the construction of new masonry buildings accounting for negligible shares. Nearly 60 % of the entire Italian masonry residential building stock is more than 60 years old and 87 % of it was erected before 1980. Hence, nearly the total share of the existing masonry residential buildings in Italy does not comply neither with the provisions issued by the 1987 first comprehensive structural design code of masonry buildings (Ministerial Decree 20/11/1987) in conjunction with the 1996 moderate seismic design code (Ministerial Decree 16/01/1996), nor with the energy efficiency requirements provided by the 1991 first Italian regulation (Law 10/1991).

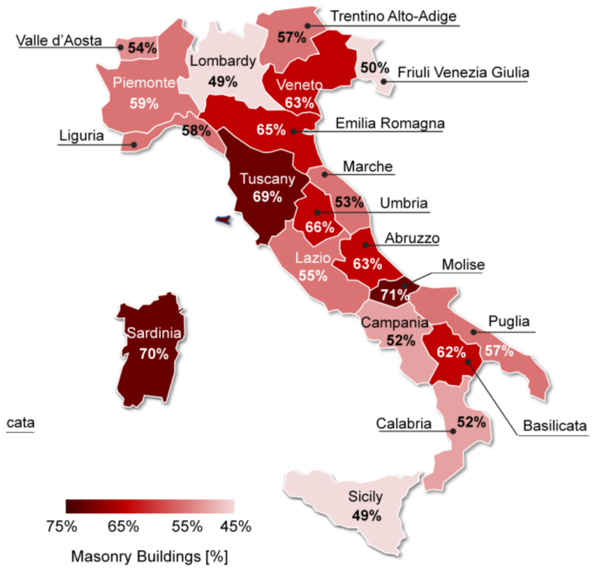
Figure 6. Distribution of Italian masonry residential buildings by year of construction



Source: Romano et al. (2023), Data – Istat (2011)

The geographical distribution of the Italian masonry residential building stock has been investigated according to two main levels: (i) by region (i.e. NUTS-2 level) and (ii) by municipality. As for the analysis at regional level, Lombardy results the Italian region with the highest number of masonry residential buildings, followed by Sicily and Veneto. The investigation of the single residential building stocks of each Italian region enables to estimate the corresponding percentage distribution of masonry residential buildings per region (Figure 7), identifying the Italian locations where the use of masonry was prevalent than other construction materials (e.g. RC, timber, steel). Molise and Sardinia account for the largest shares of masonry residential buildings with a percentage equal to more than 70 % of the entire number of residential buildings erected in either regions, followed by Tuscany, Umbria, and Emilia Romagna with shares of masonry buildings ranging into a high percentage equal to 69-65 %. Abruzzo and Basilicata also account for relevant percentages equal to 63 % and 62 %, respectively. As for the analysis at municipality level, it was pointed out that one third (i.e. nearly 35 %) of the Italian municipalities (the total number is equal to 8094) accounts for at least 75 % of the whole masonry residential building stock.

Figure 7. Geographical distribution of Italian masonry residential buildings at regional level - Percentage of masonry buildings over the total number of buildings in each region



Source: Romano et al. (2023), Data – Istat (2011)

2. **Combination of seismic and climatic zones -** The Italian territory is analysed in terms of seismic hazard and climatic conditions to provide useful information on the Italian geographical areas where the combined seismic and energy retrofit of the existing masonry building stock is most needed based on the most severe seismic-energy demand. This investigation is carried out according to a simplified-to-detailed approach leading to two level-analysis (i.e. Level 1 – simplified analysis and Level 2 – detailed analysis) identifying Italian seismic-climatic zones (SCZs). Focusing on the level 2 analysis, four SCZs based on local values of PGA and HDDs for each Italian municipality indicate various levels of combined seismic and energy demand, i.e. SCZ1 (high demand), SCZ2a and SCZ2b (moderate demand, with SCZ2a characterised by a seismic-driven demand and SCZ2b by an energy-driven demand), and SCZ3 (low demand). The distribution of masonry building for each of the SCZ above was also analysed: 18 % of Italian masonry buildings are concentrated into the SCZ1, 36 % into the SCZ2a, 24 % into the SCZ2b, and 22 % into the SCZ3. In the SCZ1 the highest number of masonry buildings is concentrated in the Italian provinces located along the Apennine areas, mainly in Abruzzo region, requiring a high combined seismic-energy demand. Furthermore, some provinces of Emilia region and northern–eastern Italian areas also result into the SCZ1 with a high percentage of masonry buildings The majority of masonry buildings concentrated in the SCZ2a are located in the provinces of central and southern Italy, where the seismic hazard is moderate-to-high and the climatic conditions are not so severe, followed by a lower percentage of buildings (about 25 %) concentrated along the Tyrrhenian coast. Conversely, the majority of masonry buildings resulting into the SCZ2b mainly refer to northern-western Italian regions, which are energy-driven areas since they exhibit significant climate conditions in terms of HDD, but a moderate-to-low level of seismic hazard. Finally, the SCZ3 includes Sardinia and southern Puglia regions accounting for the highest percentage of masonry buildings requiring low seismic-energy demand, followed by a lower percentage of buildings (about 25 %) mainly concentrated along the Tyrrhenian coast.

3. **Masonry building typologies -** The identification of Italian RC buildings needing combined renovation relies on specific seismic and energy driven investigations.

   As for the seismic investigation, data on structural typologies, age, and size, which were collected within the so-called AeDES (Agibilità e Danno nell'Emergenza Sismica, in Italian) forms for compliance with safety requirements and damage survey of ordinary buildings in post-earthquake emergency (Baggio et al., 2007) related to the 2012 Emilia earthquake (Dolce and Di Bucci, 2014), were examined. The choice of the 2012 Emilia database, included in the Database of Observed Damage (Da.O.D) platform (Dolce et al., 2019), depends on two main factors: (i) according to Step 1, 65 % of the existing residential building stock of this region accounts for masonry buildings, and (ii) according to Step 2, provinces of Emilia region result into both the SCZ1 and SCZ2a, identified by a high and moderate seismic-energy demand, respectively. Two masonry building typologies, mainly varying by period of construction, floor area, and horizontal structural elements (i.e. floors), were identified as the constructions most suffering from seismic vulnerability in the Emilia region. These typologies are potentially also indicative of the existing masonry building stock located in the north-eastern Italian areas. One building typology consists of regular layout and good quality masonry walls without tie rods/tie beams supporting (i) flexible (e.g. timber), or (ii) semi-rigid (e.g. double layer timber panels) floors. It is indicative of low-rise buildings erected before 1945, with two or three floors and a total floor area equal to 300-400 m². The other identified building typology differs from the previous one by the use of rigid floors (e.g. RC floors), the period of construction referring to buildings erected before 1971, with a total floor area equal to 400-450 m². Thrusting roofs are present in both building typologies, representing a recurrent cause of seismic vulnerability for masonry buildings.

Beyond the seismic vulnerability, these building typologies also exhibit an inadequate energy performance, as demonstrated by the values of the thermal performance of the building envelope components, retrieved by the TABULA project ([7]) database, resulting much higher than the corresponding threshold values required by the Italian regulations on energy efficiency of buildings currently in force (Appendix B of Ministerial Decree 26/06/2015 - 15A05198).

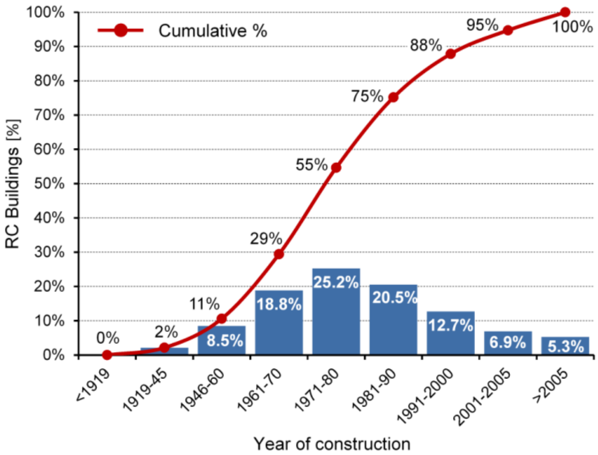
2.2.3 Italian RC buildings needing seismic and energy retrofit

Similarly to the masonry building analysis, a simplified prioritisation of the Italian RC building typologies is carried out according to a three-step procedure, as it follows:

1. **Analysis of statistics on Italian RC building stock** - Data on the age of the Italian masonry residential building stock and its geographical distribution are analysed according to the 2011 Census of the Italian Statistical Institute (Istat, 2011).

   The distribution of the Italian RC residential building stock by year of construction (Figure 8) shows that the first RC buildings were erected during the period 1919 - 1946. However, a crucial impulse to their construction occurred only after the 2nd World War by leading to a final extent of more than 300000 (i.e. 8.5 %) RC residential buildings at the end of 1960s. However, the most consistent rise of RC buildings share refers to the three following decades by reaching a peak of more than 900000 (i.e. 25.2 %) RC buildings erected during the decade 1971-1980. The analysis of these statistics points out that 75 % of Italian RC residential buildings was constructed before 1990 and only 12 % in the decade 1990-2000 with a further decrease in the two following decades. Hence, 75 % of the Italian RC residential building stock was constructed before the adoption of the first Italian regulation on energy efficiency in 1991 (Law 10/1991). Furthermore, it does not comply with the requirements of the modern seismic design code, first introduced in 2003 (OPCM 3274/2003). In addition, most of the Italian territory was not classified as seismic until 1980, when 55 % of the Italian RC residential buildings was erected.

Figure 8. Distribution of Italian RC residential buildings by year of construction, expressed in terms of percentage of buildings and its corresponding cumulative percentage

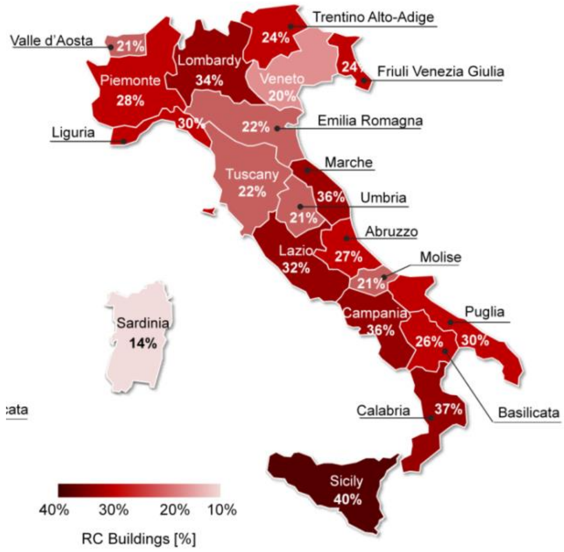


Source: Romano et al. (2023), Data – Istat (2011).

([7]) Typology Approach for Building Stock Energy Assessment' (TABULA) project (2009-2012), https://episcope.eu/iee-project/tabula/, and its dedicated web-based tool, named TABULA WebTool, https://webtool.building-typology.eu/.

The geographical distribution of the Italian RC residential building stock has been investigated according to two main levels: (i) by region (i.e. NUTS-2 level) and (ii) by municipality. As for the analysis at regional level, Sicily results the Italian region with the highest number of RC residential buildings. The investigation of the single residential building stocks of each Italian region enables to estimate the corresponding percentage distribution of RC residential buildings per region (Figure 9), identifying the Italian locations where the use of RC was more diffused than other construction materials (e.g. masonry, timber, and steel). Sicily accounts for the largest share of RC residential buildings with a percentage equal to 40 % of the total number of residential buildings constructed in this region, followed by Calabria, Campania, Marche, Lombardy, and Lazio, with shares varying into a percentage range equal to 37-32 %. As for the analysis at municipality level, it is pointed out that more than 60 % of Italian municipalities accounts for no more than 25 % of RC buildings.

Figure 9. Geographical distribution of Italian RC residential buildings at regional level - Percentage of RC buildings over the total number of buildings in each region



Source: Romano et al. (2023), Data – Istat (2011).

2. **Combination of seismic and climatic zones** – Similar observations on the analysis of the Italian territory in terms of seismic hazard and climatic conditions carried for the masonry buildings are valid for the RC ones. However, a different distribution of RC buildings by SCZ is achieved. Specifically, 14 % of RC buildings are concentrated in SCZ1 (high demand of combined seismic and energy retrofit), 43 % in SCZ2a (moderate combined demand - seismic-driven), 22 % in SCZ2b (moderate combined demand – energy-driven), and 21 % in SCZ3 (low combined demand).

3. **RC building typologies –** The identification of Italian RC buildings needing combined renovation relies on seismic and energy driven investigations.

   Research studies on seismic vulnerability assessment of Italian existing buildings, providing details on typical residential RC buildings, were analysed (Masi, 2003, Masi and Vona, 2012, Masi et al., 2015). RC framed structures designed only for gravity loads resulted into the most widespread RC structural typology in Italy, generally consisting of one-way moment resisting frames until the 1990s. Two buildings typologies most needing combined seismic retrofit to be combined with the energy one were identified based on the period of construction: (i) pre-1971 RC framed structures and (ii) post-1971 RC framed structures, mainly varying for the constitutive material properties. Both typologies are regular in plan and elevation, differentiated between small and large floor area, as well as among two-storey, four-storey and eight-storey buildings. Masonry infills play a crucial role in seismic performance of RC framed structures, thus various configurations of infill walls were considered, i.e. bare frame (ineffective infills), regularly infilled-frame, and pilotis-type frame (i.e. absence of infills at the ground floor). Both pre-1971 and post-1971 building typologies exhibited the highest seismic vulnerability in case of pilotis-type frames.

Masonry infill walls assume a fundamental role also for the energy performance of RC framed structures, thus the evolution of infills typologies from 1930s to 1990s was investigated according to the analysis provided in Manfredi and Masi (2018). Similarly to the analysis on the Italian masonry building typologies, a poor thermal performance of the infill walls was pointed out. Indeed, the values of their thermal performance during the period 1950-1990 were higher than the threshold values required by the Italian regulations on energy efficiency of buildings currently in force (Appendix B of Ministerial Decree 26/06/2015 - 15A05198).

3 Overview of seismic retrofit technologies and their classification

A brief review of suitable seismic retrofit technologies for the renovation of the EU building typologies is first presented (Section 3.1). The investigated technologies are classified both qualitatively and quantitatively by means of LCT-based criteria and a detailed cost analysis, respectively (Section 3.2).

3.1 Seismic retrofit technologies

Technologies for seismic retrofit of buildings can be classified into global and local strengthening interventions, operating at level of structural system as a whole and individual structural elements, respectively. The most used global interventions common to different building typologies are briefly presented in the following, along with local interventions analysed by building typology.

3.1.1 Global strengthening interventions

Global interventions common to different building typologies focus on technology solutions aimed at either reducing the seismic demand or enhancing the seismic capacity of a building.

The first solution (aim: reduction of seismic demand) includes the following retrofit technologies:

— **Seismic isolation** - Seismic isolation (Warn and Ryan, 2012) consists in placing horizontally flexible devices, typically at the base of the structure (i.e. base isolation), to physically decouple the motion of the structure from the ground. Thus, the seismic shock propagation into the structure is reduced, extensively minimising structural and non-structural damages, also protecting building contents and equipment. This solution is particularly effective for strategic buildings, which need to be fully operative after a seismic event, as well as for historic buildings to preserve their value (Vailati et al., 2021). Although the concept of seismic isolation dates back to more than one hundred years ago, it has only been practiced since 1980s with the development of a variety of base isolation systems, which can be classified into two main categories: (i) elastomeric bearings, and (ii) sliding systems. The first category includes various types of rubber bearings differentiating by their main properties and compounds in laminated rubber bearings and lead rubber bearing (LRB), whereas the second category encompasses devices based on friction principles.

  Laminated rubber bearings, classified as low-damping (LDRB) and high-damping (HDRB) rubber bearings, consist of alternating layers of natural or synthetic rubber and reinforcing steel plates. In case of LDRBs, significant deformation may occur during an earthquake, thus external additional damping devices need to be also installed to limit large displacements, whereas HDRBs exploit the use of special rubbers (e.g. carbon black added to the raw rubber during the mixing process) to supply significant damping, thus overcoming the LDRB drawback. Similarly, LRB devices (Robinson and Tucker, 1977, Robinson, 1982) consist of rubber and steel plates, but they also include a lead plug that is press-fit into a central hole in the bearing and serves as energy absorbing device providing high damping.

  Sliding systems rest on a single or multiple sliding interfaces with a low coefficient of friction. Isolators relying on pure friction systems lack of restoring mechanism, thus the isolated building may permanently shift from its original position at the end of a seismic event. In order to overcome this limitation, a simple system with a single sliding surface and restoration capabilities, known as friction pendulum system (FPS), was introduced in 1990s (Zayas et al., 1990). The FPS consists of an articulated slider, whose surface is coated by a special interfacial material (i.e. polytetrafluorethylen, commercially known as Teflon) to provide a suitable friction, moving on a stainless-steel concave surface. Devices with multiple – from double (Fenz and Costantinou, 2006) to more than four (Tsai et al., 2010) - sliding surfaces have been proposed as an evolution of the traditional single-FPS to provide adaptable behavior to earthquake and a reduced footprint with the same deformation capacity.

— **Additional damping** - The basic function of the passive energy dissipation devices in the form of additional dampers is to absorb or consume a portion of the energy input to a structure by an earthquake reducing energy dissipation demand on the structure and minimising structural damage. Dissipation may be achieved either directly by the conversion of kinetic energy to heat or indirectly by transferring energy among vibrating modes (Costantinou et al., 1998). The first mechanism includes both hysteretic devices, operating on principles related to either yielding of metals (i.e. metallic dampers) or frictional sliding (i.e. friction dampers), and viscous devices, operating on principles related to either fluid passage through orifices (i.e. fluid viscous dampers) or deformation of viscoelastic solids/fluids (i.e. viscoelastic dampers). The second mechanism is based on the introduction of supplemental oscillators as dynamic vibration absorbers, including the so-called Tuned Mass Damper (TMD), consisting of a secondary sliding (or suspended) mass linked to the primary structure by means of a spring, and Tuned Liquid Damper, differing from a TDM for the use of a liquid in a partially filled tank as secondary mass.

The second solution (aim: enhancement of seismic capacity of building) refers to the provision of **new seismic-resistant systems**, which encompass various technology options, as it follows:

- **RC infills and RC walls** - The addition of new RC infills to RC framed buildings is an effective intervention to significantly improve both strength and stiffness of the existing structural system (Canbay et al., 2003), as also demonstrated by feasibility studies for real buildings (Miller and Reaveley, 1996, Gregorian and Gregorian, 1996). The RC infill solution consists in transforming one (or more) span of the existing RC frame into a shear wall by filling it with RC (cast in place or prefabricated). The connection to the existing frame is made by means of studs or dowels anchored in the beams and columns and embedded in the core of the new infill wall. However, this intervention suffers from some criticalities, such as difficult and time-consuming workmanship, need to relocate occupants (Sevil et al., 2011). The seismic strengthening intervention by adding new RC walls to an existing structure follows a similar retrofit approach to the RC infill wall provision. However, RC walls are real structural walls placed inside or along the perimeter of an existing RC building. This solution provides additional stiffness to the existing structure, also leading to various benefits, such as reduction of floor drift and existing structure irregularities (both in plan and in elevation). The design of their configuration (e.g. new RC wall erected around an existing RC column, inside the existing structural grid, or as a buttress at the end of the existing structure or outside) needs to be carefully studied to avoid torsional effects. This retrofit intervention provides a high level of occupants' disruption, which can be minimised by considering the external configuration, with the new walls operating as buttress (e.g. Kaltakci et al., 2008).

- **Rocking wall systems** - Rocking walls (Qu et al., 2012, Belleri et al., 2014) are specially-detailed structural walls with finite rotating capacity at the base and large lateral stiffness, thus becoming a viable lateral load resisting system for multi-storey steel and/or RC buildings. Rocking wall structures can also affect self-centering functionality, resulting in little or no post-earthquake lateral drift. Rocking systems can be fully implemented inside existing buildings. In fact, it is possible to transform traditional elements, such as RC walls or cores (e.g. stairwells), in elements with rocking technology, thus re-centering (with no residual deformations) after a seismic event.

- **Steel wall panels** - Steel plate shear walls (SPSW) are considered an effective lateral force-resisting system in buildings due to the energy dissipating capability and high initial stiffness. Hence, this technology is used to strengthen existing RC or steel buildings. A typical SPSW consist of steel plates (webs) surrounded by boundary elements in both horizontal (beams) and vertical (columns) directions Compared to RC walls, SPSWs benefit of various advantages in terms of reduction of wall thickness and building weight, thus reducing foundations loads due to gravity and the overall building seismic load. Moreover, SPSWs are typically easier and faster to install and they are more readily repaired or replaced.

- **Exoskeleton solutions** - The exoskeleton is an "additive" system applied on the external perimeter of a building, connected to the existing structure, and equipped with its own foundations, joined or connected to the existing ones. This solution has achieved a growing interest as retrofit intervention since it enables a holistic renovation of existing buildings including energy, architectural, functional ameliorations beyond the enhancement of their seismic performance. Exoskeletons may be designed by adopting two different structural systems (Marini et al., 2017): (i) shear wall exoskeleton, providing stiffness and resistance of the new lateral force-resisting system into a number of discrete additional elements (e.g. RC walls, steel concentric or eccentric braced frames, steel wall panels), and (ii) shell exoskeletons, exploiting the entire building façades to enforce a box-structural behaviour. Hence, shear wall exoskeleton solutions rely on 2D planar systems, which can be arranged either parallel or orthogonal to the existing building (Di Lorenzo et al., 2020, 2023), whereas shell exoskeleton solutions rely on 3D spatial systems, which can be flat or curved in the form of grid (e.g. steel diagrid system) or continuous (e.g. cross laminated timber (CLT) panel layer) systems. Focusing on shell exoskeleton solutions, the steel diagrid system, introduced as a load-bearing structure for tall buildings (Mele et al., 2012), is a structural system consisting of triangular modules composed of two diagonals and a horizontal element, recently also used as global seismic retrofit solution (Labò et al., 2020). Currently, the interest in the use of CLT panels to retrofit existing buildings (Margani et al., 2020, Zanni et al., 2021) has widely grown due to its effectiveness in providing an engineered multi-layer skin able to provide a holistic renovation.

3.1.2 Local strengthening interventions

Local interventions are investigated by building typology, focusing on RC and masonry buildings, as it follows:

- **RC buildings** - Local interventions related to RC buildings refer to RC existing members (i.e. beams, columns, and beam-to-column joints) strengthening to enhance their strength, ductility, and seismic capacity by means of various retrofit technologies.

  Generally, RC beams and columns can be retrofitted by traditional technologies, such as RC jacketing (Habib et al., 2020) or steel jacketing (e.g. Braga and Gigliotti, 2006, Adam et al., 2007, Badalamenti et al., 2010), or by innovative solutions including fiber reinforced polymers (FRP) wrapping (Askar et al., 2022) or high-performance fiber-reinforced concrete (HPFRC) jacketing (Martinola et al., 2010). RC jacketing, which consists in the addition of a concrete layer (i.e. 'jacket') with longitudinal and transverse steel reinforcement outside the perimeter of an existing RC member, is recognised as one of the most common method for strengthening existing RC members (Minafò, 2015, Habib et al., 2020). Similarly, steel jacketing provides the confinement of RC members by fixing steel angles to the corners of the RC member to be strengthened and by connecting the steel angles with steel plates, welded to the corner profiles and arranged around the RC element. However, these traditional technologies suffer from some disadvantages, such as enlarged cross-section of the members and overweight in case of RC jacketing or inner surface corrosion and practice difficulty and handling in case of steel jacketing. Hence, the use of FRP-based solutions is gradually usurping the traditional retrofit interventions above. FRP are composite materials consisting of a polymeric matrix (e.g. epoxy, polyester, or vinyl ester resin) reinforced by fibers, such as glass, carbon, or aramid, with high mechanical properties and coming in the form of fabrics, sheets, or bars. The retrofit of RC beams or columns by means of FRP materials enhances their shear and flexural strength, as well as their ductility by wrapping the structural element with continuous fiber fabrics along the element perimeter. Beyond the FRP use as external bonded systems employing plates and/or sheets, a relatively newer technique, known as near-surface mounted (NSM) strengthening technique, using strips or bars has been developed to overcome debonding drawbacks (Naser et al., 2019). Although FRP solutions are corrosion-resistant, and reduce implementation time, they require skilled labour, and entail high cost, hazardous handling, and fire vulnerability (Hollaway, 2010, Lau et al., 2016). HPFRC is a composite material characterised by a cementitious matrix (i.e. mortar or concrete) and discrete fibers (e.g. metallic, polymeric, or natural) modifying the mechanical properties of the traditional concrete by improving its tensile strength, flexural strength, and ductility performance, and by counteracting crack propagation. Beyond the effectiveness in increasing the structural performance of existing RC members, the HPFRC solution also offers the possibility to ensure an adequate durability, e.g. resistance to reinforcement corrosion (Meda et al., 2016), and improved fire behaviour.

  Beam-to-column joints in existing RC buildings often feature poor transverse detailing or complete absence of transverse steel reinforcement, thus representing critical structural elements in case of a seismic event since they affect the global behaviour of the structural system in terms of strength and deformability. The seismic retrofit of RC beam-to-column joints aims to enhance their strength and ductility to ensure a ductile behaviour of the entire structure. Different technology options are available to achieve this goal, such as RC jacketing (e.g. Karayannis et al., 2008) or steel-plates jacketing (e.g. Yen and Chien, 2010), innovative solutions relying on FRP materials, HPFRC (e.g. Martinola et al., 2010), and pre-stressed high-strength steel wires (e.g. Huang et al., 2017).

- **Masonry buildings** - Local interventions for unreinforced masonry buildings include solutions aimed at mainly enhancing in-plane and out-of-plane mechanical behaviour of masonry walls (Salvalaggio and Valluzzi, 2022), typically made of stone or clay brick units bonded via mortar layer. The priority interventions to any other seismic renovation solution regard the improvement of masonry quality and continuity of masonry leaves by means of different traditional interventions, such as grout injection, repointing of walls, and reconstruction of wall portions. These solutions aim to ensure a monolithic behaviour of walls. Other local interventions refer to the use of structural coatings, by applying a thin mortar or concrete layer reinforced by high-strength fibers or meshes to enhance the tensile strength of walls. Examples of these technologies, usually being irreversible and invasive solutions, refer to both traditional solutions, such as reinforced mortar cross strips, and more recent methods adopting advanced materials. The latter include FRP solutions (Valluzzi et al., 2002), resulting more effective in their double-side configuration, and reinforced coatings, such as textile reinforced mortar (TRM) and steel fiber reinforced mortar (SFRM). TRM consists of composite based on organic matrix instead of resin, enhancing both in-plane strength and deformation capacity of the retrofitted wall (Kouris and Triantafillou, 2018, Giaretton et al., 2018), with diagonal cracking reduction. This technology results particularly promising also for retrofitting masonry infills of RC framed structures in combination with thermal insulation to provide an integrated seismic and energy retrofit solution (Bournas, 2018, Pohoryles and Bournas, 2021). SFRM coating (Facconi et al., 2020) is composed by discrete steel fibers randomly spread within the mortar matrix, considerably improving the in-plane and out-of-plane resistance of masonry walls, and resulting an effective retrofit solution even in case of single-sided strengthening (Lucchini et al., 2020).

These strengthening solutions need to be coupled with global retrofit interventions aimed at avoiding out-of-plane failure mechanisms (e.g. overturning of perimeter masonry walls) to ensure a box-like behaviour of the building (D'Ayala and Speranza, 2003), allowing the exploitation of the in-plane capacity of masonry walls. Retrofit interventions in this direction mainly refer to the provision of (i) floor/roof diaphragms and (ii) perimeter ties. Floor/roof diaphragms providing an adequate in-plane strength and stiffness ensure the distribution of the horizontal seismic actions between the earthquake-resistant masonry elements. The effectiveness of this retrofit technology mainly depends on the correct connection of the diaphragm to the perimeter walls (e.g. Lin and LaFave, 2012, Marini et al., 2018), thus inhibiting the perimeter wall overturning and favouring a global behaviour of the structure. Typically, existing historical masonry buildings are usually characterised by timber floors and roofs, which are unable to inhibit the out-of-plane wall detachment and overturning, thus extensively needing the above-mentioned strengthening interventions. The use of a thin ordinary RC slab, cast overlaying the floor extrados, connected to the floor timber joists and to the perimeter walls, is one of the most common intervention to achieve a floor diaphragm (Corradi et al., 2006, Piazza et al., 2008). However, this solution is effective only if the concrete slab solidly adheres to the existing timber structure. Moreover, it provides a significant weight increase, thus the use of high-performance RC (e.g. Meda and Riva, 2001) is preferable. The provision of FRP materials is also employed as an innovative retrofit measure to ensure a floor diaphragm, although this technology suffers from some limitations in terms of durability, removability, and compatibility. Other solutions particularly suitable also for roof diaphragms refer to the provision of a second timber deck by means of planks, placed orthogonally or diagonally to the existing one and connected to it by means of screws or nails. This overlay can be also realised with plywood (e.g. Mirra and Ravenshorst, 2021) or CLT panels (e.g. Branco et al., 2015, Rizzi et al., 2019) with steel stripes used to connect the panel to each other. The connections of the roof diaphragms to the perimeter walls used for the retrofit of historical masonry buildings can be made by means of steel dowels or studs, dry-driven into pre-drilled holes (Marini et al., 2018), which fulfil the strict compatibility requirements of historic monument preservation, as this kind of connection solution is not invasive and mostly reversible.

Historical buildings without floor and roof seismic-resistant diaphragms could be globally strengthened by using horizontal steel tie-bars, located outside or inside wall thickness. Perimeter ties could be anchored to masonry by injection or using different devices, such as steel bolted plates and pinned plates, and it is essential to prevent tie pull out failure mechanism. Specifically, perimeter ties have to ensure a resisting arch-mechanism within the masonry wall width. However, perimeter ties result into ineffective strengthening interventions for elongated buildings with large openings and devoid of floors, such as churches and theatres, or for buildings with wall discontinuity due to the presence of chimney cavity within the wall thickness, and buildings with porches or irregular plan configuration. In such conditions, roof diaphragms and their connections to walls, as described above, are necessary measures to avoid walls overturning (Marini et al., 2018).

3.2 Classification of seismic retrofit technologies

The investigated seismic retrofit technologies are classified both qualitatively by means of LCT-based criteria, and quantitatively through a cost analysis aimed at defining average cost range of the most common seismic retrofit technologies for masonry and RC buildings. Both investigations are briefly presented in the following.

3.2.1 Qualitative analysis

The attention to the renovation of the EU existing building stock based on integrated retrofit approaches by planning holistic interventions that contextually solve the multiple deficiencies of an obsolete building and reckon with the major barriers to the renovation is growing (Belleri and Marini, 2016, Passoni et al., 2021). This concept underlines the importance of considering a retrofit approach focused on the LCT principles in order to not fail in the goal of minimising impacts along the building life cycle and overcoming the renovation barriers, such as excessive disruption time, need for relocation of tenants and/or users, economic constraints. A qualitative classification scheme of the seismic strengthening interventions following the LCT principles may be useful in the first phases of retrofit design in order to facilitate the decision-making process among different retrofit options. Relevant seismic retrofit technologies are assessed according to 17 selected LCT criteria, which refer to different environmental, economic, social, and technical aspects of renovation over the building life cycle. The selected criteria are indicated by alphabet letters in Table 2, along with the definition of their corresponding minimum (i.e. 1) and maximum (i.e. 5) scores.

Table 2. Selection of LCT criteria and their minimum and maximum scores definition

	LCT criteria	Scoring 1 to 5			
A	Holistic - integrated compatibility	1	No compatible	5	Fully compatible
B	Incremental Rehabilitation	1	No compatible	5	Fully compatible
C	Disruption of the occupants/relocation	1	Relocation of occupants	5	Minimum disruption/ Short - no downtime
D	Disruption to the building, such as to the electrical and plumbing distribution systems	1	Disruption to electrical/plumbing systems	5	No disruption to electrical/plumbing systems
E	Need to replace the finishes	1	High replacement of finishes	5	No replacement of finishes
F	Construction site (prefabrication, dry technique…)	1	Wet technique	5	Dry - prefabricated
G	Duration of work	1	Long duration of on-site works	5	Short duration of on-site works
H	Repairability	1	Not possible/very difficult	5	Easy repairable
I	Maintenance	1	Very demanding maintenance in terms of time and cost	5	Low/No maintenance
J	Reusability	1	No re-usable at all	5	Fully re-usable
K	Recyclability	1	No recyclable at all	5	Fully recyclable
L	Demountability	1	No demountable at all	5	Fully demountable
M	Adaptability for future uses (long-term functionality of the building in terms of future re-planning of spaces)	1	No adaptable at all	5	Fully adaptable
N	Sustainability - Eco-friendliness	1	No eco-friendly	5	Fully sustainable
O	Aesthetics	1	Conflict with existing architecture	5	Perfectly harmonic
P	Cost of the investment	1	High initial cost	5	Low initial cost
Q	Cost over building life	1	High Life Cycle Cost (LCC)	5	Low LCC

Relevant seismic retrofit technologies are rated by assigning scores (from 1 to 5 for increasing level of LCT-effectiveness) to the selected criteria.

As for global strengthening interventions, the steel bracing systems and the external shell exoskeleton solutions result particularly LCT-effective. These outcomes are mainly due to the full compatibility with holistic renovation solutions, minimum disruption of occupants, short duration of on-site works thanks to the use of prefabricated elements, high level of recycle/re-use and demountability, low LCC. However, the CLT panel solution shows marginally lower scores than steel diagrid systems in a few criteria, resulting less compatible with incremental renovation strategy, exhibiting a more difficult reparability and requiring a slightly higher initial economic investment. The CLT panel solution results into a very promising intervention for a holistic renovation encompassing structural, energy, and architectural restyling (e.g. Zanni et al., 2021) in line with the New European Bauhaus principles.

As for local strengthening interventions, all investigated technologies in RC buildings lead to the need to relocate occupants, replace finishes, and are also affected by the impossibility of re-use/recycle intervention materials. The latter disadvantage can be overcome in case of steel jacketing for RC beams or columns and steel plates for joints, also providing beneficial solutions in terms of easy demountability. In case of masonry buildings, all examined local strengthening technologies point out similar ratings for the LCT-based criteria. Specifically, the majority of them is found to be barely compatible with a holistic renovation, requires a quite long duration of works and relocation of occupants, and suffers from the possibility to be reused or easy dismantled. However, the examined local strengthening interventions require a quite low maintenance and can benefit from a moderate initial cost and a possible low LCC.

3.2.2 Quantitative analysis

The LCT criteria-based qualitative analysis provides useful insights for a preliminary simplified assessment of each seismic retrofit technology in different aspects aimed at minimising economic, social, and environmental impacts. However, the adoption of a multi-criteria decision making analysis may be needed to obtain an unique final assessment parameter for an appropriate comparison of the various potential alternatives towards the choice of the most feasible retrofit solution. In order to simplify this pre-screening process, a quantitative classification of selected seismic retrofit technologies is proposed by focusing on the following three key issues: (i) cost of intervention, (ii) disruption time, and (iii) compatibility with energy retrofit technologies. These aspects are critical in determining the feasibility of a seismic retrofit intervention, but they must be addressed in the conceptual design phase of any renovation strategy, as well as in the definition of the possible financial model or funding requirements in support of the project. The identified seismic retrofit technologies are classified quantitatively through a cost analysis carried out in two main phases, as briefly described in the following.

3.2.2.1 First phase – Analysis of seismic retrofit projects

The first phase of the quantitative analysis focuses on the examination of 26 case studies (CS) referring to actual seismic renovation projects of masonry and RC residential and public buildings located in northern Italy. An overview of the different building typologies and the specific geographical location of each case study, hereinafter indicated with numbers CS 1 to CS 13 for masonry buildings and CS 14 to CS 26 for RC buildings, is reported in Figure 10 and Figure 11, respectively.

Figure 10. Masonry buildings - Analysed case studies (CS) in Northern Italy by building typology and location

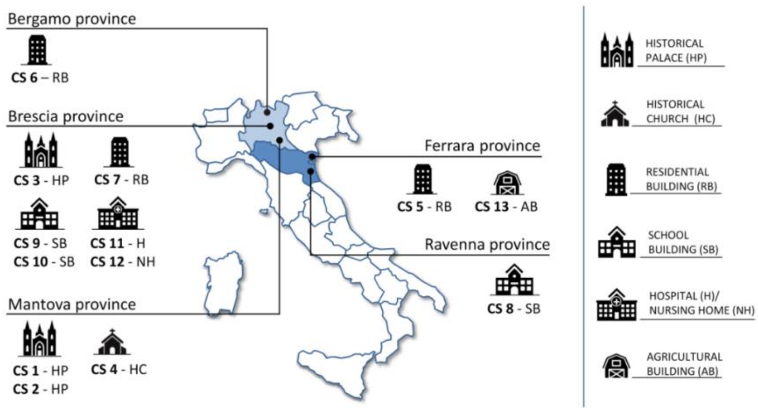
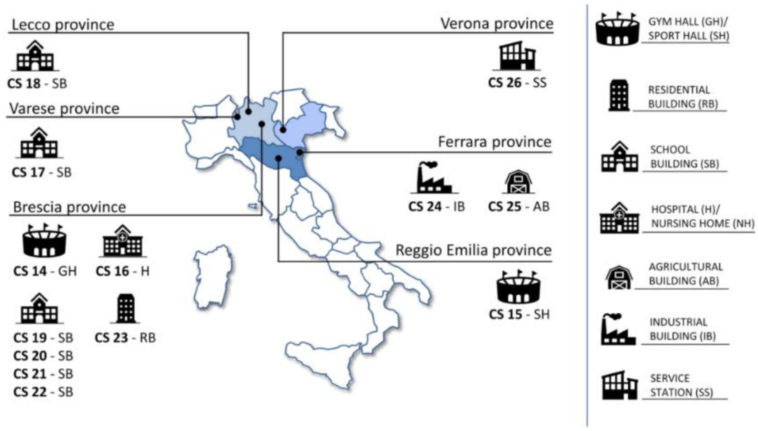


Figure 11. RC buildings - Analysed case studies (CS) in Northern Italy by building typology and location.



A synthesis of specifics related to the retrofit interventions implemented for each selected case study is reported in Table 3 and Table 4 for masonry and RC buildings, respectively.

Table 3. Masonry buildings - Main structural and energy retrofit interventions implemented in the selected case studies

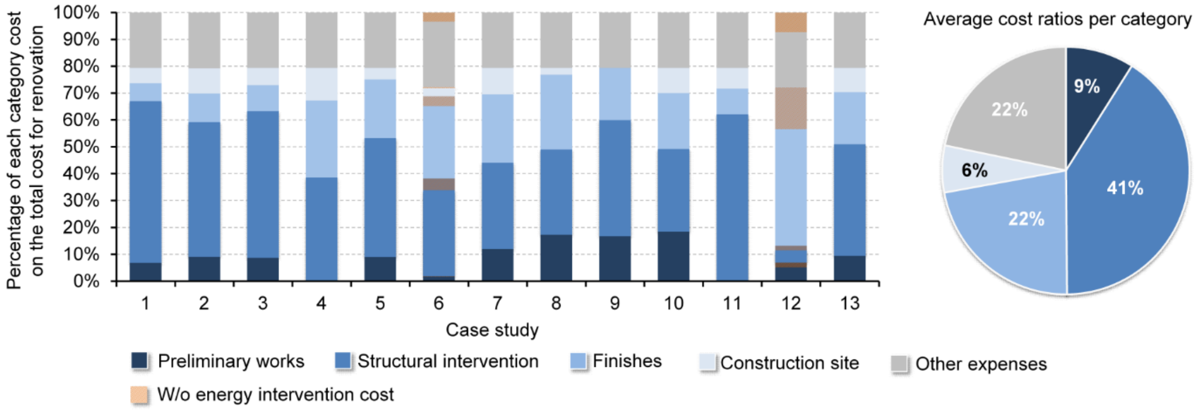
Case study	Seismic retrofit interventions					Static loads retrofit	Energy retrofit
	Quality masonry improvement	Perimeter ties	Roof/floor diaphragm	In-plane resistance of walls	Foundation system retrofit		
CS 1	✓	✓	✓			✓	
CS 2	✓	✓	✓			✓	
CS 3	✓	✓	✓	✓	✓	✓	
CS 4	✓	✓	✓	✓		✓	
CS 5	✓	✓	✓			✓	
CS 6		✓	✓	✓	✓		✓
CS 7	✓			✓			
CS 8			✓	✓	✓		
CS 9			✓	✓			
CS 10			✓				
CS 11	✓	✓	✓	✓	✓		
CS 12	✓	✓	✓	✓		✓	✓
CS 13	✓	✓	✓				

Table 4. RC buildings - Main structural and energy retrofit interventions implemented in the selected case studies

Case study	Seismic retrofit interventions				Static loads retrofit	Energy retrofit
	Joint strengthening	Exoskeleton (Shear wall)	Exoskeleton (Shell)	Roof/floor diaphragm		
CS 14			✓	✓		✓
CS 15		✓	✓	✓		
CS 16	✓	✓				
CS 17		✓				
CS 18		✓				✓
CS 19	✓	✓		✓		
CS 20	✓			✓	✓	
CS 21		✓		✓		
CS 22		✓		✓		
CS 23		✓		✓		✓
CS 24	✓					
CS 25	✓					
CS 26	✓	✓				

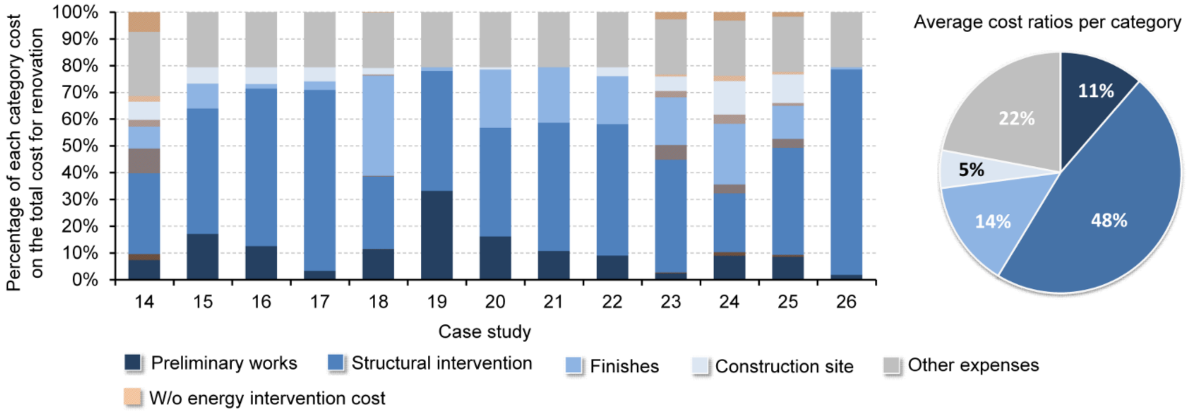
Project documents were investigated to carry out a breakdown of the total construction cost for the renovation intervention including various activities. The latter are subdivided into six main categories, namely (i) preliminary works, (ii) structural intervention, (iii) energy intervention (when implemented), (iv) finishes, (v) construction site management costs, (vi) other expenses (including contingencies, technical expenses, vat, etc.). Each cost category is expressed as a percentage on the total construction cost for renovation with the structural intervention cost category accounting for the highest percentage in the majority of investigated case studies for both masonry (Figure 12a) and RC (Figure 13a) buildings. Based on these results, the average cost ratios (expressed in percentage) of each category are estimated and the structural intervention cost categories result into the highest values equal to 41 % and 47 % of the total construction cost for renovation in masonry (Figure 12b) and RC (Figure 13b) buildings, respectively. Finishes and preliminary works are also significant expense items of the total construction cost for renovation in case of both masonry and RC buildings, unless the intervention is implemented from outside the building and the renovation technologies only include the structural elements without any external claddings (e.g. CS 16, CS 17, CS 19, and CS 26).

Figure 12. Masonry buildings – Synthetic cost breakdown by category of the total cost for renovation



(a) (b)

Figure 13. RC buildings – Synthetic cost breakdown by category of the total cost for renovation



(a) (b)

3.2.2.2 *Second phase – Average unit cost ranges*

The second phase of the quantitative analysis concerns the estimation of the average unit-cost ranges of selected seismic retrofit technologies for masonry and RC buildings. It is carried out by using the previous cost breakdowns, construction cost books with reference to the Italian market, and interviews with design professionals, experienced estimators, and construction companies. It is worth noting that results are carried out with reference to particular geometries and assumptions (i.e. construction site located in Italy, medium-size buildings, reasonable access to construction site), thus cost fluctuations can occur for different cases. Furthermore, qualitative remarks in terms of disruption time (mainly intended as need to relocate occupants) and compatibility with energy retrofit technologies are also underlined.

As for masonry buildings, the following retrofit interventions are considered: improvement of masonry quality and continuity of the stonework or brickwork; retrofit of the foundation system with various underpinning methods; strengthening of masonry walls with structural coatings, as well as with steel braced frames; introduction of a new seismic resistant structure made of shear walls, either inside or outside the building; enforcement of a box structural behaviour with floor and roof diaphragms and perimeter ties; and strengthening of vaults. The highest average unit-cost ranges (excluding preliminary works and finishes costs) refer to new RC or steel-braced shear walls outside the buildings with isolated footings (i.e. 510-880 €/m^2 or 530-910 €/m^2 of shear wall vertical surface, respectively), mainly due to the cost of the new foundation system. This retrofit technology exhibits a low level of disruption time since there is no need for relocation of inhabitants and building function downtime due to its implementation outside the building. Moreover, it provides total compatibility with energy retrofit technologies, since it may be combined with the application of thermal insulation layer. The strengthening of vaults in historic buildings by means of extrados solutions also results into quite high average unit-cost ranges, such as interventions with ultra-high tensile steel strength strips and mortar layer (350-415 €/m^2 of vault plan) or with fiber reinforced cementitious matrix coatings (365-420 €/m^2 of vault plan). In case the retrofit intervention consists in replacing the backfill with natural hydraulic lime mortar and light weight aggregates, a reduction of the average unit-cost range is achieved (265-295 €/m^2 of vault plan). The strengthening of vaults suffers from a high level of disruption time, although it exhibits full compatibility with energy retrofit technologies – e.g. it is possible to consider an integrated seismic and energy retrofit solution by using backfill to also improve thermal insulation, beyond structural performance.

As for RC buildings, the following technologies are investigated: strengthening of beams and columns with high performance material coatings or jacketing; selective infilled bay strengthening; additional shear walls, either inside or outside the building; base isolation; and strengthening of floor to improve the in-plane diaphragm action. The highest average unit-cost ranges refer to base isolation (2500-3000 €/m^2 or 3000-3500 €/m^2 in case of cut of pillars or building uplift, respectively), followed by shear walls (i.e. same results described above for masonry buildings). Base isolation intervention provides a medium level of disruption time, but it can be the trigger to further extend the renovation by also accomplishing energy efficiency.

The proposed inventory should serve as a supporting tool in the preliminary phase of the renovation design to facilitate the stakeholders' initial decisional process. Indeed, the average unit-cost ranges are intended to be used to develop budget estimates, to enable project financing and project budgets authorisation, and may prove a valuable aid for the pre-screening of eligible renovation strategies, compliant with budget restrictions, and for comparative assessment of possible renovation alternatives.

4 Overview of energy retrofit technologies and their classification

A brief review of energy retrofit technologies for the renovation of the EU building typologies is first presented (Section 4.1). The investigated technologies are analysed to first assess their compatibility with the EU building stock (Section 4.2) and to subsequently rank them (Section 4.3).

4.1 Energy retrofit technologies

Energy retrofit technologies, hereinafter indicated as energy efficiency technologies (EETs), are usually categorised as active or passive, depending on their applicability at energy system (e.g. heating, cooling systems) or building envelope level, respectively.

A total number of 20 passive EETs are classified by envelope component: (i) wall (insulation technologies, ventilated façades, green walls), (ii) floor and roof (insulation technologies, green and cool roofs), (iii) window (replacement, films, and weather-stripping), and (iv) door (replacement, and weather-stripping). Generally, the investigated EETs mainly aim to improve thermal insulation of wall (Barreira and de Freitas, 2013), floor, and roof, reduce air infiltration through windows and doors (Younes et al., 2012), and control solar gains (e.g. Pereira et al., 2022). Modern technologies, such as green wall, green and cool roofs, provide also benefits for global warming reduction and urban heat island effects mitigation, beyond enhancing the thermal performance of buildings (Santamouris, 2011, Berardi et al., 2014, Susca et al, 2022).

4.2 Compatibility of investigated energy retrofit technologies and EU buildings

The compatibility between the investigated EETs and the EU building stock is assessed. The EU Member States exhibiting high and moderate seismic hazard according to the ESHM20 are first selected. The whole group of these countries is referred to as 'target region'. The building stock in the target region is investigated through the Hotmaps ([1]) and TABULA projects by focusing on different aspects: building use (i.e. residential, and non-residential buildings), building age, construction and thermal characteristics. Residential buildings are further classified in single-family houses, terrace houses, multi-family houses, and apartment buildings. Construction and thermal performance criteria were considered to estimate the residential and non-residential (when data are available) building shares to which the identified EETs could be applied for different thermal compatibility levels, i.e. low, medium, high. The implementation of wall and floor insulation technologies, as well as internal insulation of roofs and cool roofs were found to be fully compatible in terms of construction criteria with the residential building stock in the target region. Similar considerations were also pointed out for window and door replacement and weather stripping, and window films. For instance, the external thermal insulation composite system (ETICS) for walls accounts for a high, medium, and low thermal compatibility with 12 %, 80 %, and 8 % of both apartment buildings and SFHs, and with 10 %, 58 %, and 32 % of MFHs. However, some EETs do not result fully compatible (i.e. construction compatibility) with the building stock in the target region, thus no thermal performance compatibility was also considered in this case. For instance, external insulation of flat roofs was considered no compatible in terms of construction criteria with 5 % of the apartment buildings (consequently, indicating no thermal performance compatibility with the same figure of apartment buildings), while it was found to have a low, medium and high level of thermal performance compatibility with 7 %, 71 % and 17 % of the apartment buildings, respectively. The insulation of external wall air chambers resulted into the EET with the highest share of apartment buildings, MFHs, and SFs not compatible with its implementation, as this EET can be applied only in case of cavity walls. Based on compatibility results, the investigated EETs were ranked to assess the impact in terms of potential reduced energy each technology may have on the whole building stock in the target region. The ranking score is based on both number of buildings and energy consumed by buildings each EET may affect, along with the probability each EET can be implemented. The probability values are assumed by converting the compatibility levels (i.e. 75 %, 50 %, 25 %, and 0 % in case of high, medium, low, and no compatibility, respectively). Focusing on EETs fully compatible in terms of construction criteria with the building stock, ranking results point out that the highest impact is achieved by external insulation technologies for walls, followed in order by floor insulation, door replacement and door/window weather stripping, and internal insulation and cool roofs.

4.3 Ranking of selected energy retrofit technologies

Selected EETs (i.e. 11 EETs) are ranked based on their attractiveness for potential investments to implement integrated seismic and energy renovation of residential buildings in the target region. The identified EETs are

([1]) Hotmaps project, https://www.hotmaps-project.eu/

first analysed according to a set of indicators including unitary cost of implementation, unitary energy saved, unitary cost-effectivity, disruption time, life span, and generated waste. A multi-criteria decision making analysis is carried out through the Analytic Hierarchy Process (Saaty, 1980). Unitary cost of implementation and unitary energy saving indicators are assumed as highly important, while life span and generated waste as modestly important. Ranking results are reported in Table 5. Insulation of external walls wall air chambers, internal insulation of roofs, and interior insulation of external walls result in highly attractive EETs for investment. These result depend on low cost, high cost effectivity, and low waste generated of these energy renovation technologies, although the applicability of the insulation of external wall air chambers is compatible with a low share of buildings. Replacement and weather stripping of doors/windows reveal medium rank of attractiveness, whereas prefabricated units for external wall insulation or external thermal insulation composite systems assume a low rank. These solutions result into the least preferable options mainly due to their high cost, although resulting into the highest impactful EET for energy potentially reduced by its implementation.

Table 5. Ranking of 11 selected energy efficiency technologies

Rank	Envelope component	Energy Efficiency Technologies	Attractiveness for potential investment
1	Wall	Insulation of wall air chamber	High
2	Roof	Internal insulation	High
3	Wall	Internal insulation by cladding	High
4	Roof	External insulation of flat roofs	High
5	Door Window	Weather-stripping	Medium
6	Door Window	Replacement	Medium
7	Floor	Insulation systems	Medium
8	Wall	System of façade renovation with cement panels sheathing	Low
9	Roof	External insulation of pitched roofs	Low
10	Wall	Prefabricated unit for external insulation of façades	Low
11	Wall	External Thermal Insulation Composite System (ETICS)	Low

5 Conclusions

A wide renovation of the EU existing building stock is a key-priority as emphasised by the European Green Deal to meet the climate-neutrality by 2050. The analysis of the EU existing building typologies needing an integrated renovation to simultaneously reduce their seismic vulnerability and improve their energy efficiency represents a crucial step towards the identification of technology options for an effective combined seismic and energy retrofit intervention.

The EU residential building stock was investigated by year of construction, floor area, and structural system according to available data provided by both the European and national statistical institutes, as well as the European projects TABULA and NERA. Nearly 80 % of EU dwellings were built before 1990 and more than 2 0% before 1945, thus the EU building stock is particularly ageing. Moreover, masonry and RC structures represent the EU buildings most needing upgrading. Subsequently, an analysis focused on mapping the EU territory to climatic and seismic hazard zones based on specific 2019 Eurostat heating degree days (HDDs) data and PGA range values according to the European Seismic Hazard Model 2020, respectively. Thereby, representative EU countries characterised by moderate-to-high seismic hazard and high level of HDDs have been selected, namely Bulgaria, Croatia, Greece, Italy, and Romania. Germany has been also considered to provide a more detailed analysis by including an example of an EU country with low-to-moderate seismic hazard. Specific regions within the above-mentioned selected countries has been analysed by considering several combinations of seismic hazard and climatic conditions, building age, and period of implementation of seismic codes and energy regulations. Main results underline a potential to apply combined upgrading to at least 60–70 % of the existing building stock in the selected countries. Furthermore, a focus on the Italian context pointed out that nearly 20 % and 15 % of masonry and RC buildings is located in areas with high seismic and energy demand, thus urgently requiring combined retrofit.

Seismic retrofit technologies were reviewed by focusing on global and local interventions. The overview of global retrofit strategies refers to solutions common to different building typologies, aimed at either reducing the seismic demand (i.e. seismic isolation, additional damping) or enhancing the seismic capacity. As for the latter, different solutions related to the provision of new RC walls, RC infills, steel bracing frames, rocking wall systems, and external shear wall or shell exoskeletons (e.g. steel diagrid system, cross-laminated timber (CLT) panels) have been analysed. Local strengthening interventions applied to structural members has been reviewed by building typology focusing on RC and masonry buildings. The identified technologies have been classified both qualitatively by means of selected Life Cycle Thinking criteria (e.g. holistic/integrated compatibility, occupants' disruption), and quantitatively through a cost analysis carried out by means of a two-phase approach. The first phase regards the detailed study of 26 seismic retrofit projects related to residential and non-residential masonry and RC buildings in northern Italy to analyse the corresponding cost breakdown of all retrofit activities, namely preliminary works, structural interventions, construction site management, technical expenses, and energy upgrading (when foreseen). Structural intervention cost resulted equal to 40 % and 47 % of the total cost of all retrofit activities in masonry and RC buildings, respectively. This analysis has led to the creation of a cost inventory used in the second phase of the quantitative analysis, along with construction cost books (Italian market), and interviews with design professionals, experienced estimators, and construction companies, to estimate the average cost range of selected seismic retrofit interventions for masonry and RC buildings. This inventory should serve as supporting tool in the preliminary phase of the retrofit design to facilitate the stakeholders' initial decisional process.

Energy retrofit technologies (ERTs), compatible with seismic retrofit technologies, have been classified by their application to the components of building envelope: (i) walls (insulation technologies, ventilated façades, green walls), (ii) floors and roofs (insulation technologies, green and cool roofs), (iii) windows (replacement, and weather-stripping), and (iv) doors (replacement, films, weather-stripping). The identified ERTs have been classified according to a set of indicators, e.g. unitary cost of implementation, unitary energy saved, unitary cost-effectivity, disruption time, life span and generated waste. Selected ERTs have been ranked based on their attractiveness for potential investments to implement seismic and energy retrofit of buildings in EU countries with moderate-to-high seismic hazard (according to the ESHM20). A multi-criteria decision analysis has been carried out through the Analytic Hierarchy Process. Insulation of wall air chambers and internal insulation of roofs result in highly attractive EETs for investment. Replacement of doors/windows and prefabricated units for external wall insulation or external thermal insulation composite systems reveal medium and low rank of attractiveness, respectively.

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List of abbreviations and definitions

AeDES	Compliance with safety requirements and damage assessment survey form of ordinary buildings in post-earthquake emergency (Agibilità e Danno nell'Emergenza Sismica, in Italian)
BPIE	Buildings Performance Institute Europe
CDD	Cooling Degree Day
CLT	Cross-laminated timber
CS	Case study
Da.O.D	Database of Observed Damage
Dlgs	Legislative Decree (Decreto legislativo, in Italian)
DM	Ministerial Decree (Decreto Ministeriale, in Italian)
DPR	Decree of the President of the Italian Republic (Decreto del Presidente della Repubblica, in Italian)
EET	Energy efficiency technology
ENTRANZE	Policies to ENforce the TRAnsition to Nearly Zero-Energy buildings in Europe
EPBD	Energy Performance of Buildings Directive
ESHM20	European Seismic Hazard Model 2020
ESS	European Statistical System
ETICS	External thermal insulation composite system
EU	European Union
FPS	Friction Pendulum System
FRP	Fiber reinforced polymer
HDD	Heating Degree Day
HDRB	High-damping rubber bearing
HPFRC	High-performance fiber-reinforced concrete
ISTAT	Italian Statistical Institute
L	Law
LCT	Life Cycle Thinking
LDRB	Low-damping rubber bearing
LRB	Lead rubber bearing
MFH	Multi-family house
NERA	Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation
NUTS	Nomenclature of Territorial Units for Statistics
nZEB	nearly Zero Energy Buildings
PGA	Peak ground acceleration
PS	Prioritisation score
RC	Reinforced concrete
SCZ	Seismic-climatic zone
SFH	Single-family House

SFRM	Steel Fiber Reinforced Mortar
SPSW	Steel plate shear wall
TABULA	Typology Approach for Building Stock Energy Assessment
TMD	Tuned Mass Damper
TRM	Textile Reinforced Mortar

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