ISSN 1831-9424

European Commission

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

Overview of combined seismic and energy upgrading technologies for existing buildings

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2022

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EUR 31249 EN

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EU Science Hub
https://ec.europa.eu/jrc

JRC130861

EUR 31249 EN

Print	ISBN 978-92-76-57613-6	ISSN 1018-5593	doi:10.2760/181862	KJ-NA-31-249-EN-C
PDF	ISBN 978-92-76-57612-9	ISSN 1831-9424	doi:10.2760/63090	KJ-NA-31-249-EN-N

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Pohoryles, D. A.; Bournas, D. A.; Da Porto, F.; Santarsiero, G.; Triantafillou, T., *Overview of combined seismic and energy upgrading technologies for existing buildings*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/63090, JRC130861.

REEBUILD

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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. 40% of the European Union (EU) buildings are located in seismic prone regions and were built without modern seismic design considerations. Apart from Member States with moderate and high seismic risk, such as Greece, Italy and Croatia, with a severe impact from earthquakes during the last decades (fatalities, injuries and economic losses), 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 the 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 old buildings derives by far from the operational stage of their life (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 (COM 2021/802), besides reducing greenhouse gas and carbon emissions, measures related to seismic risk and fire safety are encouraged for planning deep renovations. 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 (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 (European Commission, 2019) 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 2030 Agenda for Sustainable Development ([2]) (Resolution 2015/A/Res/70/1) and the Sustainable Development Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable".

([1]) https://europa.eu/new-european-bauhaus/index_en
([2]) 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 an overview of the technologies for combined retrofitting of existing buildings.

Acknowledgements

The work presented in this report forms part of Action 2 of the Pilot Project "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings", financed by the EU under decision C(2019) 3874 final of 28 May 2019.

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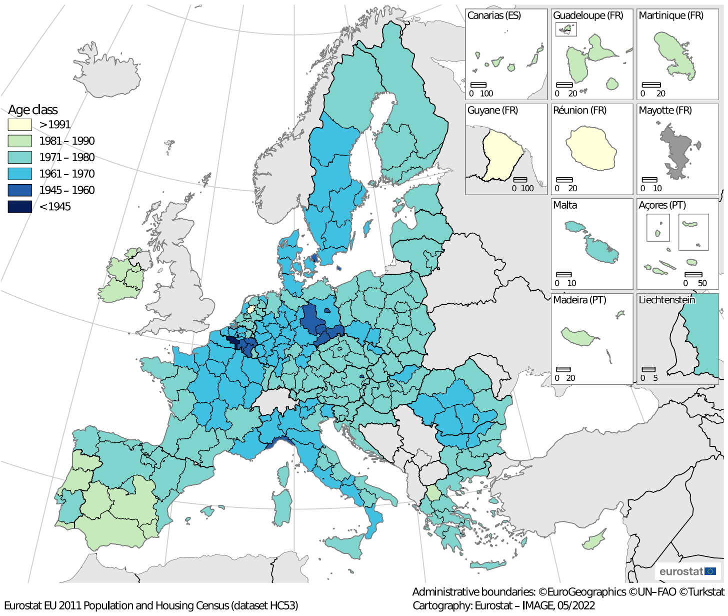
Abstract

The renovation of existing buildings plays a key role in achieving the ambitious target of climate neutrality of the EU set out within the EU Green Deal. Through increased renovation of energy inefficient buildings, a reduction in energy consumption in the building sector can be achieved, as targeted by the Renovation Wave initiative. When considering the old age of the EU's building stock, next to energy inefficiency, other, often structural, deficiencies need to be addressed. Particularly in Europe's seismic regions, recent earthquakes have highlighted the vulnerability of the EU building stock and hence the need for retrofitting. With a large proportion of EU buildings requiring renovation, recent advances in scientific and technical development show that taking an integrated approach to building renovation, a better cost-effectiveness may be achieved. Particularly in regions of moderate to high seismicity, integrating energy upgrading with seismic retrofitting interventions, may lead to cost-benefits for the building owner, hence potentially fostering higher renovation uptakes. In this report, an overview of materials and technologies that may be used for the combined or integrated retrofitting of existing buildings is presented. Identified solutions include integrated exoskeleton solutions, strengthening and thermal insulation solutions for the external walls of existing buildings, their replacement with better-performing materials, as well as integrated interventions on roofs and floor slabs. Given the novelty of this research field, a number of technologies have not yet been experimentally validated and many are still far from a potential practical application. Still, valuable insights can already be obtained and a summary analysis of the potential of different retrofitting solutions is presented here-in, including their relative effectiveness, invasiveness, disruptiveness, costs, as well as their impact on the environment. An important conclusion is that combined retrofitting offers a valuable solution for furthering building renovation, but only when further experimental research and validation of fully integrated retrofitting systems is carried out.

Executive summary

Across the EU, the median age of the building stock is higher than 30 years old, with many regions presenting a median building age above 50 years (**Figure 1**). A large proportion of EU buildings hence does not comply with current energy efficiency and seismic safety standards. To ensure a decarbonisation of the building stock, energy renovation at large scale is required, however, in seismic EU regions, this should only be carried out if the structural safety of the building at hand can be guaranteed. To achieve this, combined or integrated seismic-plus-energy retrofitting is a solution explored in the Pilot Project (PP) "Integrated Techniques for the Seismic Strengthening and Energy Efficiency of Existing Buildings", financed by the European Union (EU) under decision C/2019/3874-final of 28 May 2019. This report provides an overview of technical solutions and materials for the integrated retrofitting of existing buildings.

Figure 1. Median age of the EU building stock (occupied residential dwellings) at NUTS3 level.



Policy context

The policy context relevant to this report consists of that relevant to the modernisation of the EU building stock, hence primarily that of the Renovation Wave (COM (2020)662), supported by the establishment of a New European Bauhaus (COM (2021)573), in the context of the European Green Deal (COM (2019)640). Accelerating building renovation by at least doubling current renovation rates is seen as a key parameter to achieve the ambitious energy saving and greenhouse gas reduction targets of the EU, with the aim of achieving carbon-neutrality by 2050. Additionally, the New Circular Economy Action Plan (Communication 2020/98) was also implemented within the Green Deal, promoting life cycle thinking and circular economy principles in all major sectors. Within the built environment and construction sector, this includes life-time extension of existing buildings through maintenance, repair and renovation.

While building renovation is typically focusing either on addressing structural safety or the energy performance of existing buildings, the recent amendment of the Energy Performance of Buildings Directive 2018/844 (European Parliament and Council of the European Union, 2018), additionally promotes including measures related to fire safety and seismic risks, when planning long-term renovation strategies (LTRS) of the Member States, as these affect the lifetime and hence sustainability of buildings.

Ensuring resilience of existing buildings and infrastructure to man-made and natural hazards is the target of the Union Civil Protection Mechanism, UCPM, (Decisions 2013/1313/EU, 2019/420), which aims to reduce vulnerability and minimise exposure to elements at risk through cooperation and knowledge sharing between member states for risk mitigation. The Action Plan on the Sendai Framework for Disaster Risk Reduction 2015–2030 (SWD 2016/205) additionally encourages investment in disaster risk reduction and integrating "Build Back Better" principles for a more resilient built environment. The principles of reducing vulnerability and improving resilience is also extended to our built cultural heritage. The importance of safeguarding the built heritage was also set-out as an important target within the European framework for action on cultural heritage (SWD 2018/491).

Within this policy context, the holistic renovation approach explored in this PP aims to improve the energy performance of existing buildings, while at the same time improving the resilience of the EU building stock against natural disasters and respecting circular economy principles by enhancing its sustainability from a life-cycle perspective. By renovating buildings in an integrated fashion, next to reducing energy consumption, reducing damage and losses from future earthquakes, the environmental impact of buildings can also be reduced by limiting waste generated by building demolition works or repair works associated to seismic damage. As shown in **Figure 2**, integrated retrofitting can hence be seen to lie at the nexus between the different policies presented here, where an integrated approach allows to encompass energy efficiency measures, promotes circularity principles within the construction sector, improves the resilience of buildings and can be applied to protecting the built heritage.

Figure 2. Combined retrofitting at the nexus of relevant policy domains.

Source : Pohoryles and Bournas (2021)

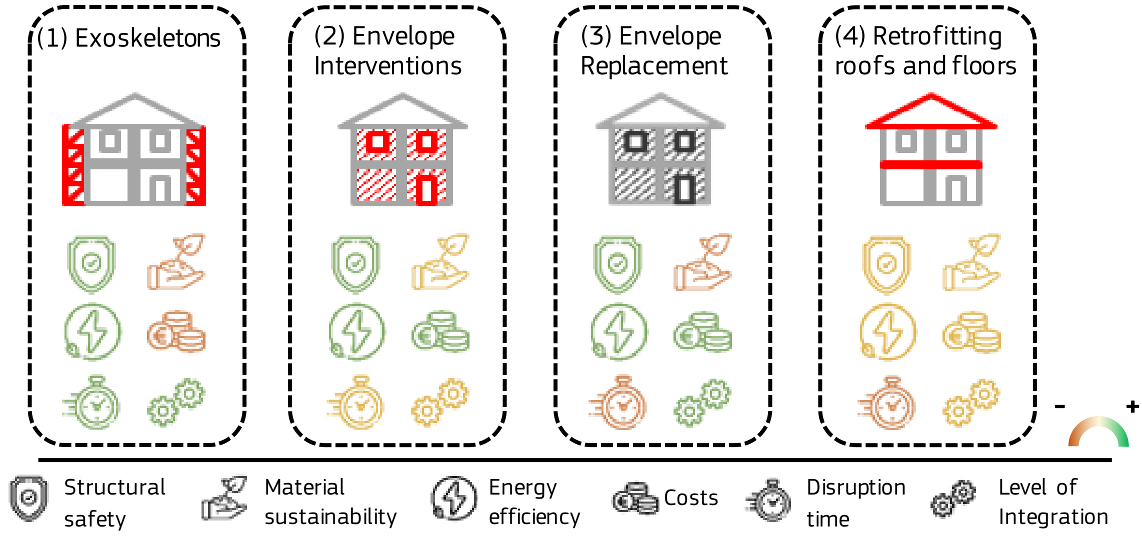
Key conclusions

- Economic feasibility studies have highlighted the potential economic benefits of combined retrofitting compared to energy upgrading alone in at least moderately seismic regions of Europe. Combined retrofitting may hence be seen as a potential solution for accelerating building renovation across EU Member States.
- A review and analysis of combined and integrated seismic and energy retrofitting solutions highlights four main types of interventions: (1) integrated exoskeleton solutions; (2) integrated interventions on the existing building envelope; (3) replacement of the existing envelope with better performing materials; and (4) interventions on horizontal elements.
- The applicability and effectiveness of the encountered solutions depends on the type of building at hand, for instance depending on the possibility of changing the appearance of the structure (e.g. built heritage), the location of the structure (e.g. densely built-up urban areas or rural areas), the current state and the type of construction of the existing building.
- The different solutions encountered have different levels of technological maturity. While some solutions have only been contextualised or evaluated numerically for their application in combined retrofitting (e.g. diagrid exoskeletons or cross-laminated timber panel retrofits), other solutions have already been tested and validated experimentally (e.g. cement-based composites plus thermal insulation retrofitting). Further experimental research is required in all cases for the retrofit schemes to become viable renovation solutions, as in most cases the seismic performance and energy efficiency improvements have been tested only separately.
- There is a need to research, test and develop new avenues for fully integrated retrofitting systems. Since the renovation of the existing building stock needs to start imminently, realistic and easy-to-adopt applications will be much more likely to have an actual impact.

Main findings

Four different avenues for combined or integrated seismic and energy retrofitting were encountered in the scientific literature and were analysed in this report. A summary of these can be found in **Figure 3**.

Figure 3. Evaluation of four different avenues for combined seismic and energy retrofitting.



Exoskeleton solutions are external auxiliary structures with their own foundation system, which can be connected to existing buildings to improve their energy efficiency and structural performance. Different types of exoskeleton have been investigated for combined retrofitting applications, ranging from diagrids, over insulated reinforced concrete frames and walls to external steel structures. Exoskeletons can support or can be combined with various technologies (e.g. solar panels, thermal insulation, green walls etc.) for improving the energy performance of the building. The energy performance of the retrofitted building can hence be tuned to any desired level. In general, however, these solutions are more costly and less sustainable then the other encountered options.

Envelope interventions include different strengthening solutions for external walls of existing buildings, such as the use of composite materials, prefabricated panels (either timber- or cement-based), or strengthening solutions for existing wall openings with structural window frames. These strengthening solutions can be combined with different thermal insulation materials and/or replacement of existing windows, to achieve an adequate thermal performance of the external building skin. Particularly in the case of composite materials and precast panels, a number of experimental and numerical studies have already been carried out, highlighting their high potential in improving both the structural and energetic performance of existing buildings. Costs can be kept low if such interventions are carried out from the outside of the building, and depending on the materials used (e.g. timber), a very sustainable retrofit solution can be provided.

An alternative to envelope strengthening is the replacement of existing deficient exterior walls. This method is only applicable to structures where walls are not load-bearing, hence not for masonry buildings. An advantage of replacing the existing envelope is that often any desired energetic performance can be achieved, and the structural behaviour can also be improved by replacing the weaker existing walls by stronger or more deformable once. Various modern brick solutions have been investigated experimentally, both for achieving a stronger and stiffer behaviour, but also for reducing the interaction between the walls and the existing frame. While any of these solutions provide high compatibility for combined or integrated renovation (e.g. by filling bricks with thermal insulation materials or using bricks with low thermal transmittance), however these have not been tested as integrated retrofitting solutions yet. Moreover, replacing outer walls is associated with a high level of building occupancy disruption and creates additional demolition waste, hence making this solution more invasive and less sustainable then the previous.

Finally, retrofitting floors and roofs of an existing building is often required in older buildings, both from the structural safety and the thermal performance point of view. Only few combined retrofitting solutions have been studied to date, and these have remained at the conceptual stage only. These include the use of a thin-folded shell combined with ventilating layer for existing wooden roofs, but also the use of timber panels combined with thermal insulation for replacing floors and renovating roofs in existing masonry buildings.

Improvements in seismic and energy performance through interventions on horizontal members alone can be considered low to moderate in effectiveness, and would normally be combined with interventions on exterior walls. Additionally, the works associated with floor and roof strengthening or replacement are significant and affect building occupancy for longer periods of time.

Overall, while research into materials and technologies for the integrated structural and energy retrofitting is still limited, valuable results and insights have already been obtained. With further experimental research and validation through applications on existing buildings, the potential of such technologies will be further demonstrated.

Related and future JRC work

Next to the activities of the pilot project "Integrated techniques for the seismic strengthening and energy efficiency of existing buildings" or REEBUILD presented here-in, other related JRC activities include:

- iRESIST+ (Innovative seismic and energy retrofitting of the existing building stock) is the first JRC project that proposed and explored the concept of integrated renovation of buildings. Within iRESIST+ different technical solutions for combined seismic and energy retrofitting were developed and are being tested experimentally on full-scale buildings at the JRC's European Laboratory for Structural Assessment (ELSA) Reaction Wall facility. Moreover in the framework of the iRESIST+ activities, the following competitive Exploratory Research (ER) and Marie Skłodowska-Curie Action (MSCA-IF) sub-projects were developed:
    - SPECTRUM and STRETCH Marie Skłodowska-Curie Fellowships (MSCA-IF): Both develop hybrid structural-plus-energy retrofitting solutions together with structural health monitoring (STRETCH) tailored for masonry cultural heritage building envelopes.
    - JRC-KOCED collaboration: The international collaboration between the JRC and the Korea Construction Engineering Development Collaboratory Management Institute (KOCED CMI) was launched in 2019. The project SEP+ investigates the use of novel prefabricated Textile Reinforced Concrete panels with integrated capillary tubes for integrated retrofitting through testing at the experimental facilities of KOCED.
    - NOTICE-EUB: A novel timber-based retrofit system for the integrated renovation of existing buildings by exploiting the high structural performance of the emerging cross-laminated timber (CLT) technology combined with advanced insulation materials.
    - ER project PINN FLOED: A bottom-up building stock assessment tool will be prepared in the PINN FLOED project at the JRC, in which the energy efficiency and seismic vulnerability of existing EU buildings will be assessed by means of physics-informed neural networks
- A framework for safe and sustainable construction has been proposed within the SAFESUST project at the JRC.

Quick guide

In **Section 1** of this report, a general introduction to the topic of integrated seismic and energy retrofitting is given. A state-of-the-art review of different combined and integrated seismic-plus-energy retrofitting methods is then presented in **Section 2**. Here the retrofit solutions are categorised into (1) exoskeleton solutions, (2) integrated interventions on the existing building envelope, (3) replacement of existing walls and (4) interventions on roofs and floors. This is followed by a brief summary in **Section 3**, providing comparisons between the different intervention technologies in terms of their effectiveness, costs, disruptiveness and invasiveness, as well as taking into account their environmental impact. Finally, **Section 4** provides the Conclusions to this report.

1 Introduction

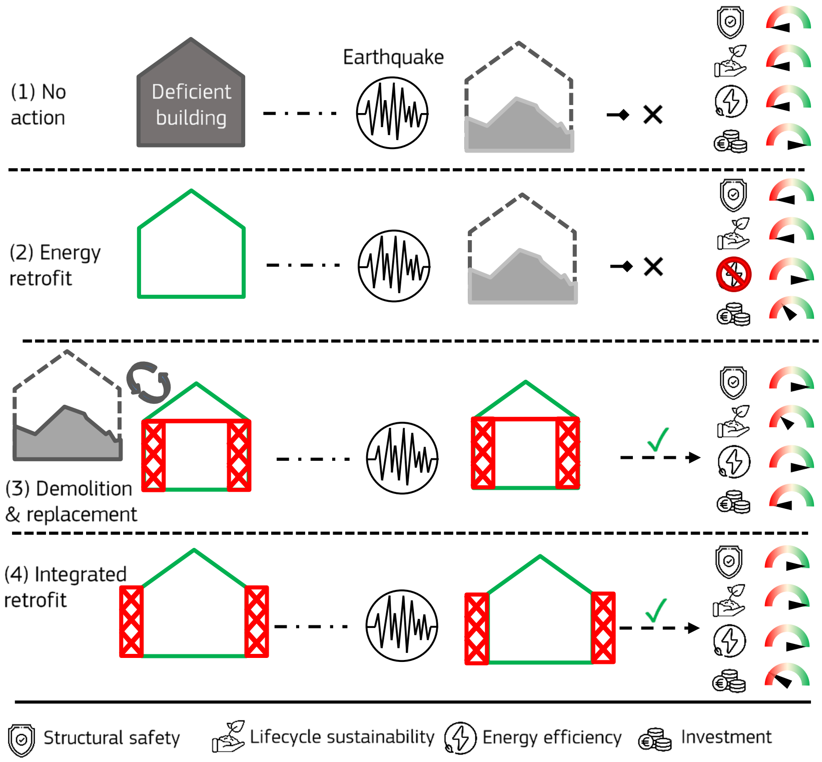
The majority of residential buildings in the EU were constructed during the post-World War II period (1945-1969), with almost half of the EU building stock (49%) older than 50 years old (eurostat, 2011). A large proportion of buildings were hence built when no strict energy regulations were enforced (Economidou et al., 2011), they hence present deficiencies in terms of their heating and cooling energy performance, including (1) inadequate or complete lack of insulation (in both walls and roofs); and (2) inefficient fenestration surfaces (windows with low thermal resistance). These lead to high energy consumption and low thermal comfort, with buildings accounting for 40% of the total EU energy consumption (European Commission, 2019) and 7.4% of EU citizens not able to keep their home adequately warm (eurostat, 2019), respectively.

To overcome this, energy retrofitting is an investment that can often be achieved at reasonable costs and with an immediate effect (Corrado and Ballarini, 2016; Salvalai et al., 2017). Within the European Green Deal (Communication 2019/640), the need for renovating public and private buildings was hence emphasised (European Commission, 2020). The old age of the building stock however also means that a considerable percentage of it has been constructed to outdated building codes and seismic standards (Palermo et al., 2018). More than three quarters (77%) have been built before 1990 (EUROSTAT, 2011) and hence before the first edition of modern seismic codes (e.g. Eurocodes) were published. This poses a great societal risk, as potential structural damage does not only lead to significant economic losses, but also severe injuries and loss of human lives, as shown by recent seismic events (Di Bucci et al., 2021). As more and more buildings approach the end of their conventional service life, material durability related risks emerge as well (Köliö et al., 2014; Bru et al., 2018). Therefore, the need for structural retrofitting should not be directed only to earthquake-prone areas, but to any kind of structure in need.

It is evident that a large portion of existing buildings in the EU present deficiencies in both energy and seismic performance. As illustrated in **Figure 4**, not taking action requires the lowest investment but is not a sustainable option, as the buildings would remain energy inefficient and are at risk to severe damage or collapse. Renovation efforts are hence required, however, until recently, these concentrated on only upgrading the energy efficiency, without taking into account structural safety. It is however important to consider that an energy upgrade investment might not be effective and may be completely lost when applied in a building of questionable structural integrity, and hence vulnerable to structural damage, e.g. due to an earthquake. This way of thinking started changing when the damage and collapse of energy-upgraded structures were observed after seismic events (Belleri and Marini, 2016; Bournas, 2018a; Bournas, 2018b), leading to loss of the energy retrofitting and loss of sustainability, as shown in **Figure 4 (2)**.

A possible avenue to reduce energy consumption and mitigate seismic risk is the demolition and complete replacement of existing deficient buildings (**Figure 4 (3)**). This may be a feasible approach for individual buildings, however at the building stock scale, such a drastic measure would have a severe impact on society, the existing urban fabric and would not be financially feasible, as it is associated to high investment costs. Additionally, demolition and reconstruction leads to significant construction waste and use of materials, which in the context of the New Circular Economy Action Plan (COM(2020)98), is not sustainable from a life cycle perspective**.** Preference should instead be given to the lifetime-extension of existing buildings, which may be achieved through combined or integrated structural and energy upgrading (**Figure 4 (4)**).

Figure 4. End of service life of buildings: The effect of (1) No action; (2) Energy upgrading; (3) Demolition and rebuilding and (4) integrated energy and seismic upgrading in zones of seismic hazard.



In the scientific literature, the topic of integrated retrofitting has gained traction only over the last few years. Next to having a beneficial impact from a life-cycle perspective, as structural retrofitting ensures the building's structural integrity and hence protects the applied thermal retrofitting (Belleri and Marini, 2016), combined retrofitting was found to have significant economic cost-benefits in regions of moderate to high seismic hazard (Calvi et al., 2016; Bournas, 2018b; Gkournelos et al., 2019; Pohoryles et al., 2020). While the evidence for the need for combined retrofitting is apparent and is acknowledged in the scientific literature, it is important to understand which materials and technologies already exist or have the potential to be developed in the near future.

This report hence aims to give an overview of the state-of-the-art of technologies proposed for the combined or integrated retrofitting of existing buildings. This brief report should be seen as a summary, while more detailed technical information can be found in (Pohoryles et al., 2022b; Pohoryles et al., 2022a). Different combined and integrated seismic-plus-energy retrofitting methods are presented in **Section 2**, categorised into (1) exoskeleton solutions, (2) integrated interventions on the existing building envelope, (3) replacement of existing walls and (4) interventions on roofs and floors. This is followed by a summary in **Section 3**, providing comparisons among the effectiveness, costs, disruptiveness and invasiveness, as well as taking into account the environmental impact of the different technologies.

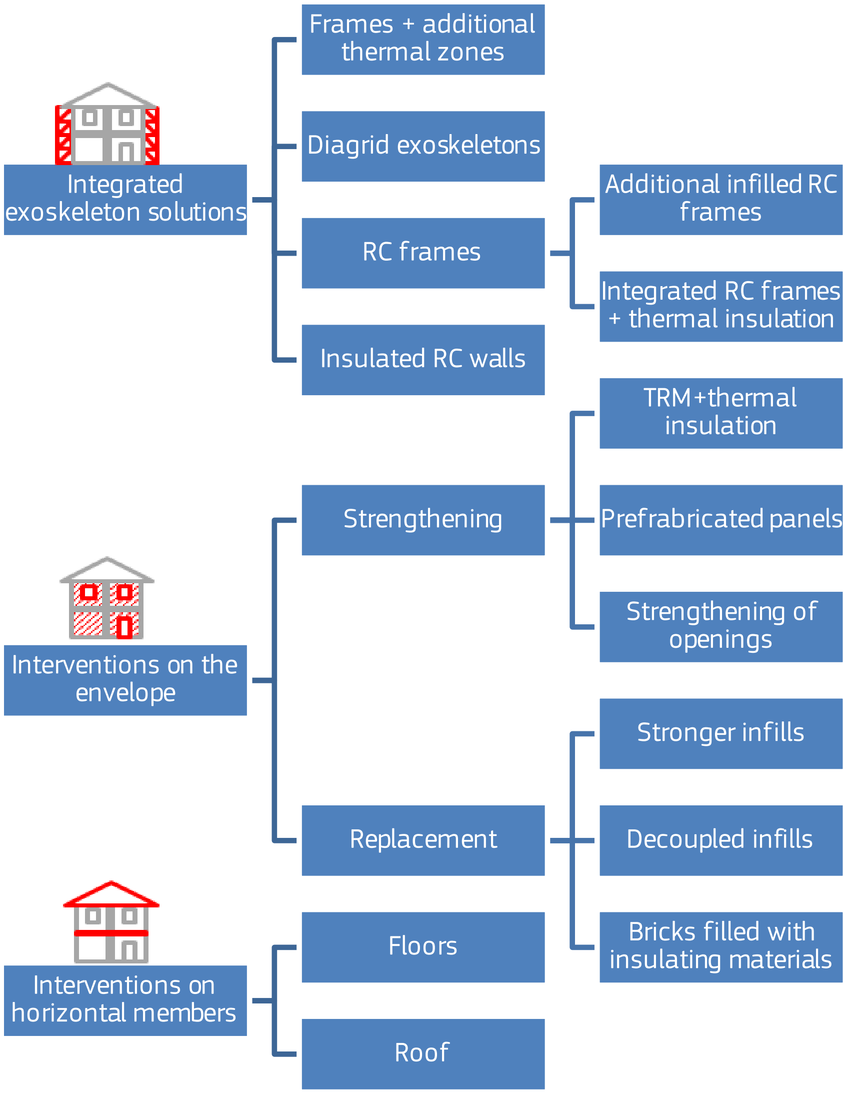
2 Integrated seismic and energy retrofitting technologies and concepts

In the following subsections, a brief review of the state-of-the-art of combined and integrated retrofitting solutions is presented. **Figure 5** aims to provide an overview and categorisation of the identified technologies[3]. For a more in-depth presentation and analysis of the presented solutions, the reader is referred to a technical report prepared by the authors (Pohoryles et al., 2022a).

Despite research into combined seismic and energy retrofitting being a relatively new field, several directions have already been explored and different technologies have been proposed and are currently being tested. Different types of integrated seismic-plus-energy retrofitting solutions are proposed in the scientific literature and can be grouped into:

- Exoskeleton interventions (Section 2.1);
- Integrated interventions on envelope elements (Section 2.2);
- Replacement of envelope elements by higher performance elements (Section 2.3);
- Combined Interventions on horizontal elements, i.e. roof and floors (Section 2.4).

Figure 5. Categorisation of combined retrofitting technologies.

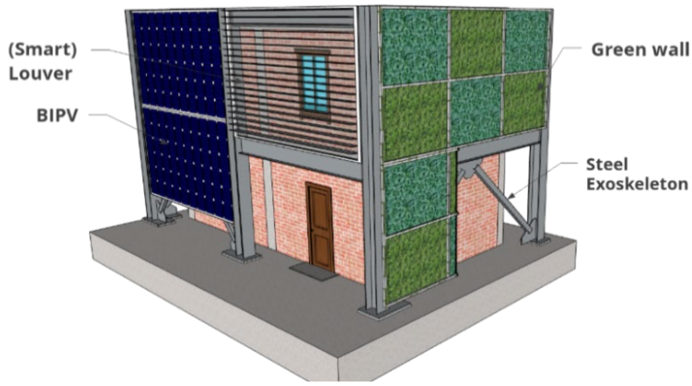


[3] While not all the interventions presented in this chapter are fully integrated systems, the studies selected display a certain degree (or show strong potential) of integration between the structural and energetic components.

2.1 Integrated exoskeleton solutions

An exoskeleton is an external self-supporting system (i.e. with its own foundations) connected to an existing building (Martelli et al., 2020), particularly suitable for the seismic retrofit of existing vulnerable reinforced concrete (RC) buildings with low dissipative capacity[4]. From a structural point of view, exoskeletons can provide additional strength and stiffness to an existing building. In recent years, the use of exoskeleton solutions for integrated retrofitting, i.e. coupling structural and energy interventions, has gained momentum (e.g.: Marini et al., 2016; Labò et al., 2016; Manfredi and Masi, 2018). **Figure 6** highlights energy-efficiency systems that could be integrated within a structural exoskeleton, which would serve as a secondary envelope. For instance, the exoskeleton could be used to support renewable energy production (e.g. building integrated photovoltaics, BIPVs), or vertical gardens (so-called "green walls") that contribute to passive cooling, and solar shadings, e.g. louver systems, that provide control over solar radiation and natural lighting (D'Urso and Cicero, 2019).

Figure 6. Integration of exoskeletons with different energy-efficiency systems.



In **wall-like solutions**, the additional stiffness and resistance are lumped into few elements placed perpendicular to the building façade, such as RC shear walls or steel bracing systems. For combined retrofitting, Marini et al. (2017) proposed the use of steel-braced shear wall exoskeletons for seismic performance improvements on which energy efficiency systems can be supported. The latter includes solar greenhouses along the southern façade, as well as thermal insulation (e.g. expanded polystyrene, EPS), new windows and shading systems (adjustable louvers) for solar radiation control. The use of steel or timber frames which can provide energy-efficient buffer zones, helping to reduce solar radiation in summer, providing solar heating in winter, and supporting plug-and-play installations for new Heating, Ventilation, and Air Conditioning (HVAC) systems have also been investigated (Ferrante et al., 2018). The frames can additionally increase living space (balconies or extra rooms) and enhanced architectural value and user comfort. Finally, Foti et al. (2020) built a prototype dissipative frame element, to be used as a modular "kit" that allows to seismically retrofit a building (through the installation of buckling-restrained axial dampers) and produce renewable energy through photovoltaic panels supported by the frame.

In **shell exoskeleton systems**, the energy efficiency upgrade and structural safety could be achieved through a dual-use of the same elements. The first integrated retrofitting applications appears to be the pioneering work by Takeuchi et al. (2005; 2006; 2009) on "**integrated façades**", consisting of the combined application of a shell exoskeleton, using Buckling Restrained Braces for seismic strengthening that can act as shading devices for reduced solar gains, leading to improved seismic safety and reductions in cooling energy consumption up to 10.7% (Misawa et al., 2016).

Optimised **diagonal steel grids ("diagrids")** for integrated retrofitting of RC buildings may be seen as an evolution of this initial idea, with recent proposals by Labò et al. (2016; 2020a; 2020b) and D'Urso and Cicero (2019). From the structural point of view, the diagonal members are designed to transfer and dissipate seismic forces from the building floor diaphragms to the diagrid and its foundations. The diagrid retrofit can then be easily combined with other façade elements (e.g. solar modules, vegetation, insulation or shading), as illustrated in **Figure 7**, to offer integrated solutions for structural, energy and architectural improvements. The latter is of special interest in the context of the New European Bauhaus initiative, bringing together sustainability and high aesthetics. Another advantage of diagrids from a life cycle perspective is the possibility of using reusable, repairable, adaptable and fully demountable elements.

[4] Masonry buildings are less compatible with exoskeletons due to their higher stiffness, hence needing robust auxiliary structures to subtract a significant amount of seismic forces from the existing structure.

Figure 7. Different design options for a holistic upgrading of RC building with a diagrid exoskeleton.

Source: D'Urso and Cicero, 2019 (CC BY 4.0).

Rather than using steel-based shell exoskeletons, Manfredi and Masi (2018) proposed the use of additional **external RC frames** combined with masonry infill walls to improve the thermal transmittance of the building envelope. In more demanding climatic zones, these infill walls can be complemented with other energy efficiency solutions. The external RC members can be designed to provide adequate strength and stiffness according to local seismic requirements. Note that instead of a cast-in-place external RC frames, precast auxiliary RC frames, such as the High-Performance Dissipating Frame system (Manfredi et al., 2021; Manfredi et al., 2018), may also be used, reducing labour time on site.

Pertile et al. (2018; 2019; 2021) recently developed and tested an external shell system, which consists of a thin RC wall cast in-situ between pre-assembled layers of insulating material, functioning as permanent formwork (**Insulated Concrete Formwork**). It is suitable for both masonry and RC buildings and is conceived to be applied only on the external side of the building, to lower the disruption caused by the temporary relocation of tenants during the intervention works. The RC wall is the structural part of the system, providing adequate seismic resistance to the existing structure, while the formwork provides additional thermal insulation to the building envelope. A similar solution has been proposed by Pozza et al. (2021), where a tightly spaced, cast-in-place external RC frame system is combined with prefabricated EPS modules, which provide the formwork for casting the RC frame, as well as being the energy retrofitting component, acting as a double-skin for the existing building.

It is important to consider however, that for any of the proposed solutions, building an exoskeleton is not always feasible, e.g. due to lack of space in the case of densely built-up areas (Santarsiero et al., 2021). Furthermore, as the seismic forces are typically transferred from the existing building to the exoskeleton by means of connections at the floor level, exoskeleton interventions may not be effective when the horizontal diaphragm is not stiff. An additional limitation for exoskeletons is the significant change of the external appearance of structure, causing the highest architectonical impact, which may render the intervention inapplicable for certain types of buildings (e.g. cultural heritage buildings).

However, in the cases where the application of exoskeletons for building renovation is possible, it can generate benefits of reducing building occupant disruption (being applied outside only), minimising post-earthquake building downtime, elongating the building structural service life and reduce the environmental impact associated with seismic damage over the building life cycle (Marini et al., 2017). When the constitutive elements of steel-braced exoskeletons or precast RC auxiliary frames are easily demountable and repairable, additional benefits throughout the building life-cycle are generated. Moreover, exoskeletons give the possibility for adding new storeys or balconies and to change the external appearance of the building and hence its aesthetics. This makes the exoskeleton solution of particular interest to the New European Bauhaus initiative (COM (2021)573).

2.2 Integrated interventions on existing building envelopes

Many combined renovation strategies target the existing vertical building envelop elements (e.g. infill walls or structural masonry), as these typically contribute largely to their vulnerability and energy transmittance. In such interventions, a structure can be strengthened by intervening on the existing envelope while the addition of thermal insulation can contribute to reducing energy consumption. In the scientific literature, three main intervention avenues have been identified: (1) application of composite materials; (2) use prefabricated panels (cement-based or timber-based), or finally (3) the local strengthening of the existing openings integrated with upgrading of the old fenestration.

For all envelope strengthening solutions, a careful evaluation of the foundation and frame elements needs to be carried out, as the increase in base shear capacity and a potential increase in shear forces acting on the existing frame, mean that additional strengthening may be required. Within the context of the New European Bauhaus, it is also interesting to note that the proposed retrofitting solutions can be combined with different modern cladding solutions to modernise the architectural appearance of a building.

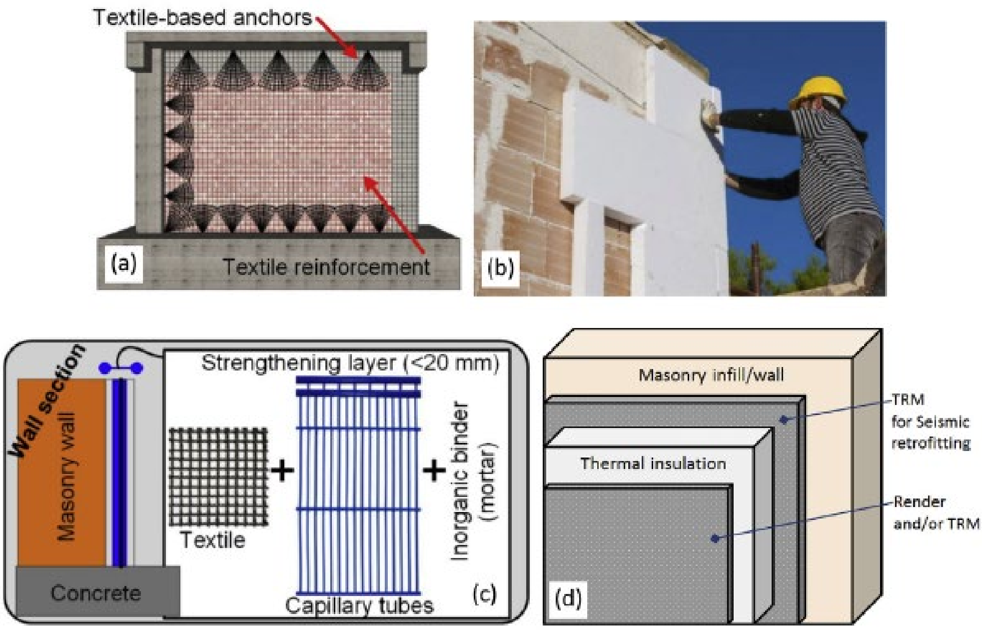
2.2.1 Strengthening of existing infill or masonry walls with composite materials

Given that the existing building envelope of older RC and masonry buildings are often structurally and thermally deficient, an obvious choice for combined retrofitting is strengthening and insulating external walls of these buildings. Of particular interest are well-tested strengthening solutions using composite materials, which can improve the structural integrity of exterior walls. A summary on the use of such materials in seismic strengthening is provided in (Pohoryles and Bournas, 2020a; 2020b; 2021).

Composite materials for structural strengthening range from textile-reinforced mortars (TRM), fibre-reinforced polymer (FRP) sheets, which are bonded using epoxy raisins and engineered cementitious composites (ECCs) or steel fibre reinforced mortars (SFRM), using short fibres dispersed in a mortar, to steel meshes for reinforcing thin layers of plaster. TRM, made of (high strength) lightweight textile fibre reinforcement (e.g.: carbon, glass or basalt) combined with cementitious mortars, has gained much attention in recent years for their use in integrated seismic and energy retrofitting of building envelopes.

As shown in **Figure 8**, Bournas (2018b) explored the avenues of TRM for structural-plus-energy retrofitting solutions, proposing the combination of TRM with different, conventional or advanced, thermal insulation materials (e.g. TRM + Polyurethane (PUR), TRM + Extruded polystyrene (XPS), TRM + Aerogels, etc.), or the integration of capillary tube heating systems within the TRM. Different combinations can be used to provide improvements in structural, energy and (potentially) fire behaviour in one integrated application. Such a system can be used both in framed buildings (RC, steel) with masonry infills and in load-bearing masonry structures.

Figure 8. Possible configurations of TRM and energy upgrading solution: a) Infills and RC structure retrofitting with TRM, b) Insulation of a building envelope, c) TRM + capillary heating tubes and d) TRM + thermal insulation material

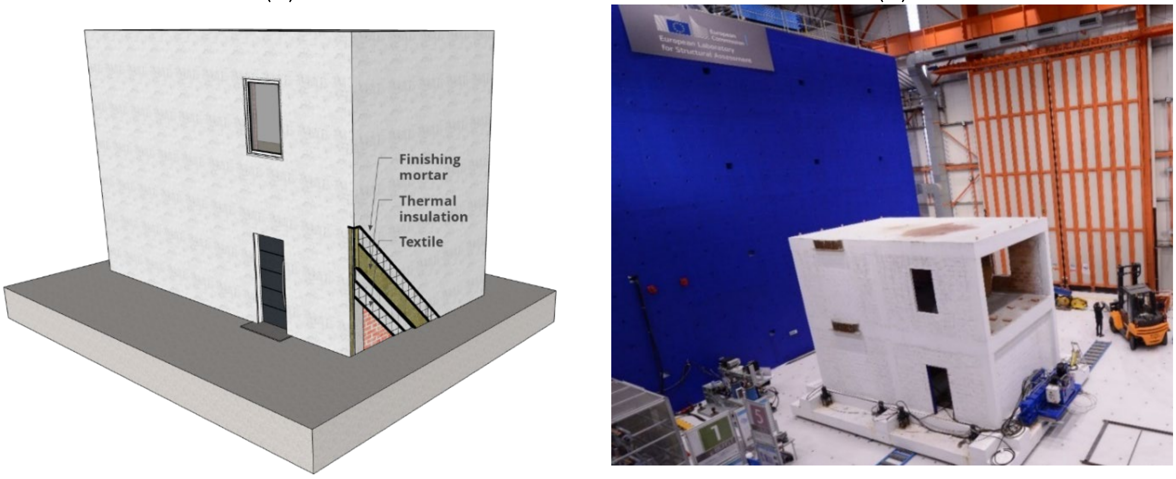


Source: Bournas, 2018 (CC BY 4.0)

Numerous experimental studies on the applicability of TRM or SFRM with thermal insulation have shown the adequacy of such solution for the combined retrofitting of existing RC (Baek et al., 2022) masonry buildings (e.g.: Triantafillou et al., 2017; 2018; Giaretton et al., 2018; Gkournelos et al., 2020; Karlos et al., 2020; Facconi et al., 2021). These studies have also highlighted the good behaviour of TRM and thermal insulation at increased temperatures, as well as under in- and out-of-plane loading. This type of solution is also currently investigated on a full-scale building currently undergoing testing at the JRC's ELSA laboratory within the iRESIST+ project (Pohoryles and Bournas, 2021; Kallioras et al., 2022), as shown in **Figure 9**.

Figure 9. (a) iRESIST+ combined retrofitting with TRM and thermal insulation. (b) Prototype structure at the ELSA facility of the European Commission, Joint Research Centre (JRC).

(a) (b)



The economic feasibility of combined TRM and thermal insulation solutions was evaluated by Bournas (2018) and Gkournelos et al. (2019), showing that an integrated retrofitting system is more cost-effective in the long run compared to an energy upgrade solution alone, especially for structures with higher seismic risk (vulnerable structures or high seismic hazard). Applying TRM at the same time as thermal insulation in a combined retrofit can be considered more cost effective then separate energy and seismic interventions, as it reduces labour time and construction costs, both in terms of scaffoldings and surface preparation.

Pohoryles et al. (2020) assessed the effect of this combined retrofitting scheme with respect to reducing CO_2 emissions of the EU building stock by applying different annual renovation rates (1, 2 and 3%). The building stock of twenty European cities with different seismic hazard (five seismic zones) and climatic conditions (four climatic areas) was assessed through a combined seismic and energy performance analysis. In order to achieve ambitious energy saving and greenhouse gas reduction targets for 2030, it was found that the current average renovation rate of 1% has to at least triple (3%). To achieve such acceleration in renovation rates, it was highlighted that the integrated approach is more cost-effective in locations of medium to high seismicity compared to energy retrofitting alone.

A further addition to the cost-effectiveness of TRM-based solutions is the possibility to be applied on the external side of existing infill walls only[5], which would avoid downtime and residents' relocation. The external intervention, however, modifies the façade of the building, which may not be suitable for buildings of architectural and historic value, or located within historic centres. For existing RC buildings this is very often not an issue or may even have a positive impact on the building regeneration from an aesthetic point of view.

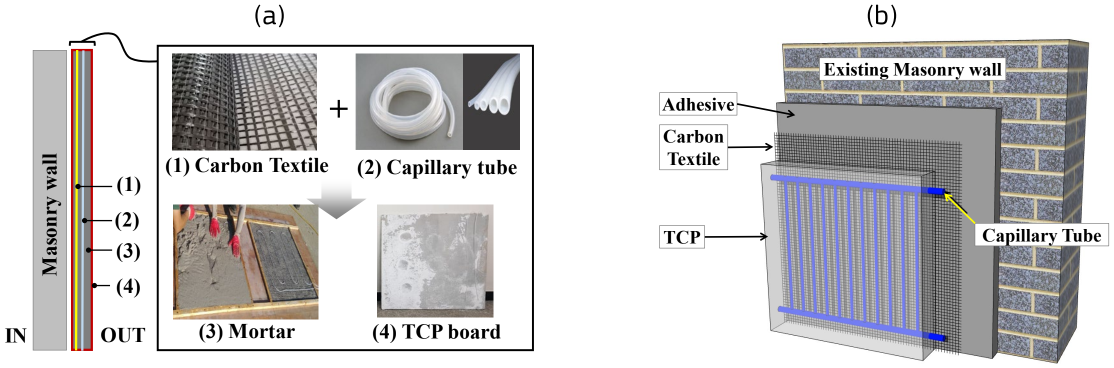
2.2.2 Prefabricated integrated panels

An alternative integrated retrofitting approach for existing external walls is the use of prefabricated panels. These can be configures to achieve seismic strengthening and energy upgrading at the same time in the same intervention. The advantage of prefabricated panels compared to the previously described strengthening techniques is that they can be applied faster onsite, reducing the time and cost of the intervention. Two general types of panels can be differentiated: (1) cement-based panels; or (2) timber based panels.

Textile-based **precast retrofit panels** (Textile and Capillary tube Composite Panel or TCP) have been investigated in the framework of the international joint research collaboration projects iRESIST+ and SEP+[6] between the JRC and KOCED CMI[7]. As shown in **Figure 10**, a capillary tube system for active heating of walls, is attached to a carbon textile, used for strengthening, and embedded in a layer of mortar to produce a precast panel (Choi et al., 2020; Bae et al., 2021; Baek et al., 2022). Instead of capillary tubes, Sousa et al. (2021) created precast sandwich panels using thermal insulation (XPS or EPS) within thin faces of recycled-steel-fibre reinforced mortar.

[5] Depending on the initial seismic performance of the building and the quality of masonry, a double-sided intervention may be required.
[6] SEP+: Development of Textile-reinforced mortar & Capillary tube Panel retrofitting technology to simultaneously improve **S**eismic and **E**nergy **P**erformance of the existing buildings
[7] Korea Construction Engineering Development Collaboratory Management Institute

Figure 10. TCP combined seismic and energy retrofitting panel, (a) composition; (b) application on a masonry wall.



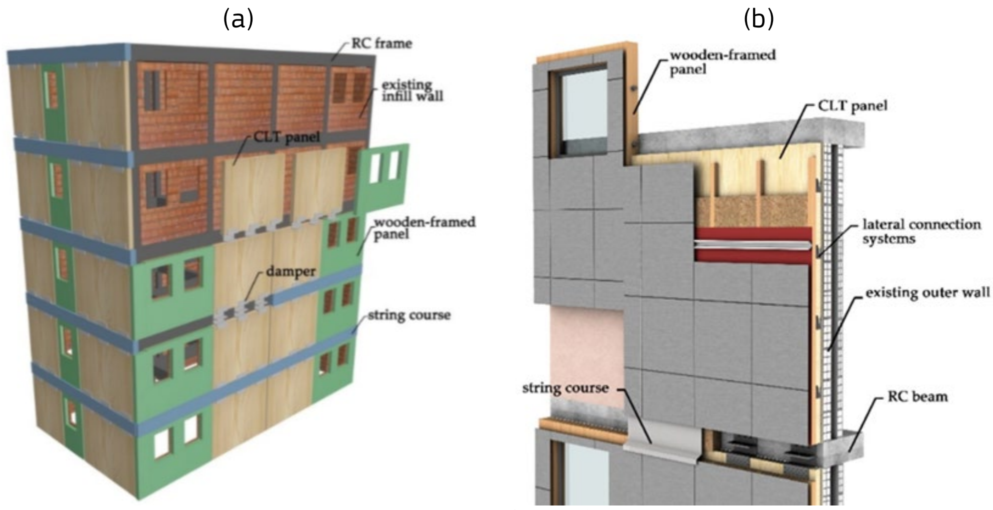
Source: Baek et al, 2022 (CC BY 4.0).

Instead of pre-cast cement-based panels, **engineered timber solutions** such as cross-laminated timber (CLT) panels and oriented strand boards (OSB) have recently gained traction for their use in integrated seismic and energy systems for either RC buildings (Stazi et al., 2019; Margani et al., 2020; Smiroldo et al., 2021) or load-bearing masonry buildings (Dalla Mora et al., 2015; Valluzzi et al., 2021; Busselli et al, 2021). In the framework of sustainable and resilient construction, timber presents important properties: high structural strength, good thermal insulation, sound absorption, low weight and ease of assembly (reducing on-site work and building downtime), full recyclability and reduced embedded-CO_2 (Asdrubali et al., 2017; Nocera et al., 2018).

The use of CLT infill walls for the seismic and energy retrofitting of RC buildings has been conceptualised by Stazi et al. (2019), where the proposed retrofit achieves increases in overall lateral stiffness of existing RC frames while at the same time, improving energy efficiency through external insulation (PUR panels) directly connected to the 3-ply CLT panels. In **Figure 11**, a similar proposal by Margani et al. (2020) is shown, where prefabricated CLT panels are connected to masonry infill walls using seismic energy dissipation devices to achieve a combined energy, seismic and architectural renovation of existing RC buildings. Energy upgrading is achieved by adding a layer of bio-based insulation materials (e.g. hemp, cellulose, sheep wool etc) within the panels, and by providing new high-performing windows and a ventilated façade system. Note however that these systems are still in a conceptual phase and have not yet been tested.

The use of prefabricated panels generally reduces onsite work and hence also the associated downtime, while the invasiveness of such interventions is dependent on the possibility to carry out the works from the outside of the structure. The effectiveness of the prefabricated panels in strengthening a building depends on the reliability of the structural connections between the panel system and the original structural elements, which may require additional works if the substrate quality is very low, hence prolonging the duration of the intervention, increasing costs, depending on the selected ancillary intervention.

Figure 11. CLT panels used as external reinforcement in RC frames: (a) Components of the proposed retrofitting system; (b) External installation of prefabricated timber panels with ventilated façade system.

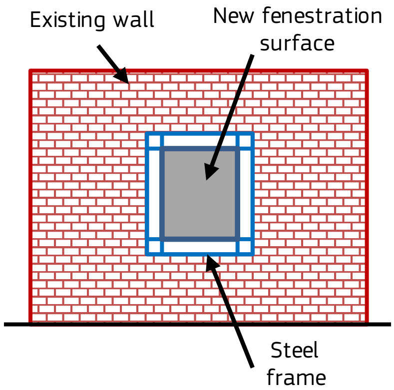


Source: Margani et al. 2020 (CC BY 4.0).

2.2.3 Strengthening of openings with structural frames with fenestration replacement

Particularly for unreinforced masonry (URM) buildings, integrated retrofitting of masonry walls with openings (e.g. for windows or doors) through replacing old windows and doors while also introducing a steel frame for strengthening the opening (**Figure 12**) may be particularly suitable. Structural steel window frames have been recently shown to improve the seismic behaviour in tests on individual masonry wall specimens (Proença et al, 2019; Oña Vera et al., 2021). The auxiliary elements work in parallel with walls and provide a beneficial confining effect to the surrounding masonry, increasing the in-plane shear strength and stiffness of the existing masonry wall. An alternative to the structural steel window frame solutions are hybrid CLT and load-bearing laminated glass façade elements (Žarnić et al., 2020).

Figure 12. Strengthening of openings with structural frames with fenestration replacement.



The combination of structural interventions with the complete substitution of fenestration with low-emissive and airtight ones, may lead to improvements in energy efficiency and structural performance. The area concerned by the retrofit works is limited around the openings, reducing demolition and reconstruction works. Disruptiveness can be substantial, as the relocation of occupants and activities in the units affected by the works is needed. If fenestration replacement is not foreseen, other types of seismic and energy retrofit of the building may be more effective. Finally, it has to be considered that the intervention effectiveness still needs to be tested further and may be limited depending on the initial state of the masonry walls.

2.3 Replacement of envelope elements with better performing materials

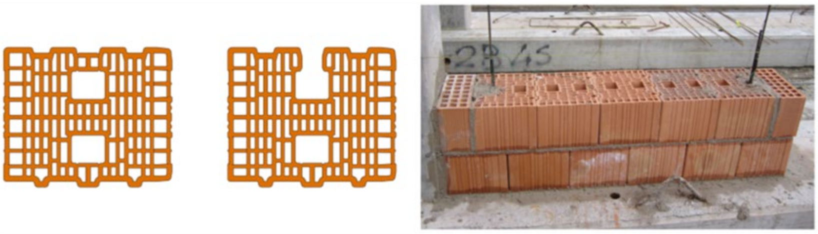
When strengthening interventions on envelope elements, e.g. masonry infill walls, are not practically or economically feasible, or the envelope presents poor quality construction or damage, then their replacement may be an alternative in the case of RC or steel framed structures. Despite their increased invasiveness and disruptiveness, envelope replacements may also be economically viable in cases when a retrofit would require interventions on structural elements associated with the need for partial demolition of existing infills.

Replacing existing infill walls with more (seismic and energy) efficient elements allows to improve the performance of the building to any desired level. Structurally, an infill wall replacement can achieve (1) an increased stiffness and strength, or (2) increased deformability of the frame through reducing infill-frame interactions. At the same time, the energy performance can be enhanced through the use of brick units and/or mortar with better thermal transmittance, and/or the addition of thermal insulation. Independently of the approach taken, the use of masonry units filled with insulating materials (e.g.: styrofoam) can enhance the energy performance without adding thickness to the wall. This also includes brick units filled with more advanced materials, such as aerogels (Wernery et al., 2017) or phase change materials (PCMs), which can be used for passive thermal control (e.g.: Kant et al., 2017; Saxena et al., 2020).

2.3.1 Replacement with stronger and stiffer elements

The replacement of outer infill layers has been proposed by Masi et al. (2017), in which thicker and stronger clay bricks with a lower thermal transmittance, are combined with an external insulation layer. Artino et al. (2019), similarly proposed to replace the external layer of double-leaf infill walls with better-performing Autoclaved Aerated Concrete (AAC) blocks and thermal insulation.. Replacing existing unreinforced masonry infill walls with steel reinforced masonry constructed from thick perforated clay units, which provide a more adequate thermal and acoustic performance, as shown in **Figure 13**, has been investigated experimentally by da Porto et al. (2020). The replacement with more robust clay masonry infills has shown reduced in-plane damage and increased in-plane strength.

Figure 13. Replacement of existing envelope by reinforced masonry (RM) infill walls.



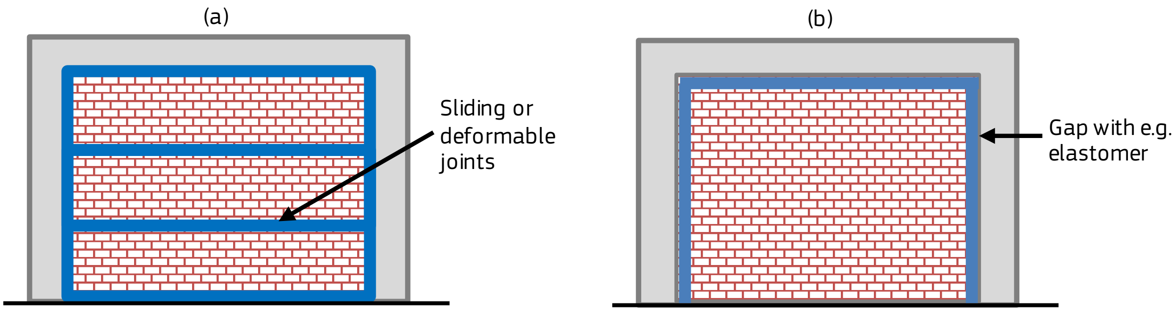
Source: da Porto et al., 2020 (CC BY 4.0).

Independent of the type of masonry used for replacement, replacing only the external layer of the existing wall can limit the level of disruption by ensuring operations are carried out mainly from the outside of the building. Additionally, it is however important to consider that additional strengthening of the existing frames and foundations may need to be considered when replacing infills with stiffer ones, as the maximum base shear sustained by the building will increase.

2.3.2 Replacement with deformable or decoupled infill walls

To avoid the issue of increased base shear or potential damage to the RC frame, an alternative option for infill wall replacement are infills (1) fitted with deformable or sliding joints or (2) decoupled from the frame, as illustrated in **Figure 14** (a) and (b), respectively. Instead of increasing the stiffness and strength of the frame, a more ductile behaviour with higher deformability, closer to that of a bare frame structure, can be achieved.

Figure 14. Replacement with decoupled infills: (a) using sliding joints; (b) provision of a gap.



In the first case, the masonry infill is split into subpanels, separated at the mortar bed joints through e.g. special horizontal sliding joints (e.g.: Morandi et al., 2018), vertical sliding surfaces (e.g.: Vintzileou et al., 2016) or both horizontal and vertical special deformable joints (e.g.: Verlato et al., 2016). As for section 2.3.1, the new infills can be constructed from modern clay brick units to provide adequate thermal and acoustic characteristics, as well as enhanced durability (Morandi et al., 2018). A mortar-free infill system, in which the brick units are connected through joints made from recycled plastic instead of mortar has been proposed by Vailati et al. (2018) , where the joints are designed to additionally support thermal insulation panels (e.g. EPS).

The alternative approach in **Figure 14** (b) uses a layer of soft and deformable materials between the frame and the masonry enclosure to uncouple the infill panel and reduce infill-frame interactions, hence controlling damage. An example includes cellular polyethylene strips used to isolate infills from steel (Tsantilis and Triantafillou, 2018a) or RC frames (Tsantilis and Triantafillou, 2018b), which was shown to eliminate frame-infill interaction and prevent damage for small to medium levels of drift. These cellular materials are however fully compressed during larger intensity earthquakes, i.e. when in-plane drifts increase, allowing to activate the infills and increasing the strength and stiffness of the tested frames. Marinković and Butenweg (2019) applied a similar approach using elastomers along the sides and top of the infill walls, constructed with highly thermally insulated clay bricks.

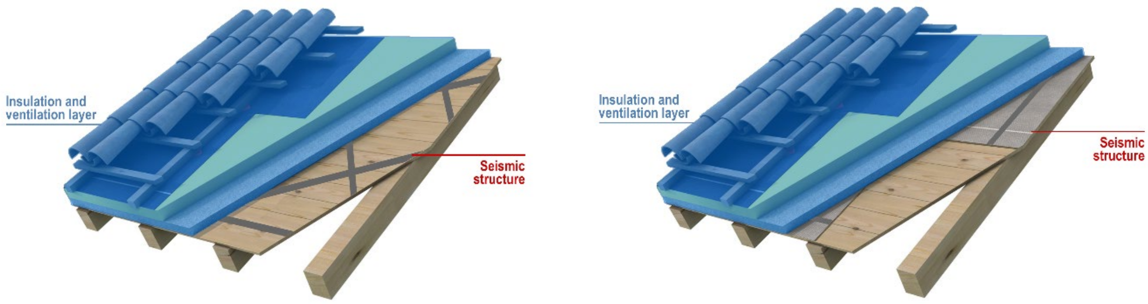
2.4 Interventions on floor diaphragms and roofs

In older buildings, and masonry buildings in particular, floors and the roofs are often made from timber joists and wooden planks or one-way steel beams with large flexural deformability and low in-plane stiffness, requiring stiffening interventions for an improved seismic behaviour (Gattesco and Macorini, 2008). At the same time, in older buildings these elements are often not (or inadequately) thermally insulated. To overcome this, combined interventions on horizontal elements could be particularly compatible in the sense that the invasiveness, spatial overlapping and scale of application is very similar for both seismic and energy upgrades. Despite this, *specific* technologies for the integrated retrofitting have not yet been investigated.

Giuriani et al. (2016) proposed a technique for the recovery of historic wooden roofs similar to the schematic view presented in **Figure 15**. The retrofit consists of a thin shell overlaying the existing roof pitch rafters and planks. Each pitch plane is transformed into a diaphragm composed of pitch joists, by perimeter chords and by web panel overlaying the existing planks. To ensure energy improvement a ventilating secondary structure is added. Basiricò and Enea (2018) combined steel hooping as structural intervention on a roof with the use of insulation panels for energy upgrading the existing historic structures.

Finally, in the Nested Building retrofit (Valluzzi et al., 2021) it was proposed to substitute existing floor slabs with CLT floors, hence reducing the seismic mass of the structure, as well as providing thermal insulation. Similarly, the existing roof structure can be demolished and rebuilt or be complemented by an internal CLT+thermal insulation layer.

Figure 15. Schematic views of the thin-folded shell combined with ventilating layer for existing wooden roofs.



The invasiveness and disruptiveness of interventions on the horizontal elements of a building, however, are generally high, particularly in the case of intermediate floors. Relocation of residents is always needed for interventions on floor diaphragms, and, depending on the side of intervention (intrados or extrados), it is often necessary to relocate residents of two different floors simultaneously. For interventions on the roofs, downtime may be reduced and the relocation of residents may be avoided, depending on the presence of an attic floor and according to the type of intervention, i.e. if the intervention is carried out above the existing structural layers or not.

3 Comparison of identified technologies

In this Section, a brief comparison of the effectiveness, costs, level of invasiveness and downtime, as well as the environmental impact of the identified retrofitting strategies is presented. This comparison is however only *indicative* and is by no means proposed for the time being as a decision-making tool for selecting retrofitting options. The presented information is based on a detailed evaluation of combined and integrated retrofitting technologies (Pohoryles et al., 2022a).

In **Table 1**, different criteria for comparing the retrofit technologies are summarised. Note that this table should not be seen as a means to select integrated retrofitting technologies, but rather as an overview of the current state of development of said technologies. Improvements in seismic safety and energy efficiency are classified by level of effectiveness reported to date. Note that next to improvements in thermal transmittance, integrated retrofitting strategies may also be coupled with other techniques to increase the energy efficiency of a building (e.g. integration of photovoltaics, replacement of heating/cooling system, etc.).

The evaluation of relative costs and environmental impact was performed on a three-storey RC building serving as a baseline for analysis. The environmental impact of the proposed technologies was evaluated through a simplified assessment[8] of embodied carbon (cradle-to-gate) of the materials only, i.e. excluding the embodied carbon of transportation and retrofit construction (along with potential demolition and waste). The simplified analysis should hence be seen as illustrative only, and not comparative among the integrated techniques.

Next, the level of invasiveness is considered as the degree to which the existing building appearance and characteristic is affected, hence providing a measure of architectonical and functional impact. Solutions with lower invasiveness are hence those that affect the character and appearance of the building less. Typically, the higher the invasiveness (and cost) of the intervention the higher its effectiveness. For a specific application, this should be calibrated through a cost-benefit analysis. Instead, the level of disruptiveness reflects the duration of the intervention, business downtime and the necessity for residents' relocation. Here, the least disruptive interventions are those related to the construction of new structural elements or those reinforcing existing facades (outside the existing structure) devoted to absorbing seismic actions or providing thermal insulation. Finally, the type of integration between the seismic and the energy retrofit is also presented, indicating if seismic plus energy retrofitting is achieved by a single element (integrated) or two elements working in parallel (coupled).

Table 1. Summary comparison of different seismic-plus-energy retrofitting strategies.

	Structural upgrade	Energy upgrade	Costs	Impact on environment	Invasiveness	Level of disruption	Level of Integration
Exoskeleton systems	+++	+++	High	Medium-High	High	Low	Coupled/ Integrated
TRM+ thermal insulation	+++	++	Low	Medium	Medium	Low-Medium	Coupled/ Integrated
Strengthening of openings	+	+	Medium	Medium	Medium	Medium	Coupled
Timber-based panels	++	++	Medium	Low-Medium	Medium	Low-Medium	Coupled/ Integrated
Replacing envelope	+++	++	Low	High	High	Medium-High	Integrated
Interventions on floors or roof	+	+	Medium	Medium	Low-Medium	High	Coupled

[8] Details of the calculations and data used can be found in (Pohoryles et al., 2022a).

4 Conclusions

Within the EU Green Deal, the recent launch of the Renovation Wave initiative has put importance on increasing building renovation rates to achieve significant reductions in CO_2 emissions from the built environment. Energy renovations alone may however not be sufficient, particularly in the seismic regions of Southern Europe, as shown by recent earthquake events which have caused significant economic losses due to damage to the vulnerable elements of the building stock. To tackle the seismic vulnerability and energy efficiency of older deficient buildings, both structural and energy upgrading is hence required.

A number of economic feasibility studies have highlighted the potential economic benefits of **combined retrofitting** compared to energy upgrading alone in at least moderately seismic regions of Europe. To achieve combined or integrated retrofitting, a number of materials and technologies have recently been proposed in the scientific literature, and a review and analysis of recent developments was presented in this report. Four main types of interventions were identified: (1) integrated exoskeleton solutions; (2) integrated interventions on the existing building envelope; (3) replacement of the existing envelope with better performing materials; and (4) interventions on horizontal elements. A brief comparison of their costs, invasiveness and related business downtime, as well as the environmental impact of the materials used was also presented.

The first category of solutions investigated are **exoskeletons**, which include shell-grid solutions, from simple braces combined with solar shading, to material-efficient diagonal steel grids (diagrids) integrated with different kinds of thermal panels (BIPV, shading or thermal insulation). Other integrated exoskeleton solutions include the addition of insulated RC walls, as well as RC frames integrated with thermal insulation panels or with masonry infills. In shear wall exoskeletons the energy efficiency intervention, e.g. green facades, photovoltaics or shading devices, can instead be supported by the external structure and may also be used to increase the existing living space. Exoskeletons may not always be applicable, as they require an additional foundation system and often additional space around the building. Such solutions also significantly change the external appearance of structure, which may not be possible for certain buildings, but in other cases it may be a desirable architectural upgrade, e.g. in the context of the New European Bauhaus.

For masonry and RC buildings a number of **integrated interventions on their existing building envelope** have also been found in the literature. The most mature approach, with several experimental validation studies, is the strengthening of external walls with composite materials (in particular TRM) which can be combined with thermal insulation within the same intervention. Structurally, TRM-retrofitting of URM walls and masonry infills can significantly improve their in and out-of-plane capacity. TRM-based integrated retrofitting brings the advantage of external application and low disruptiveness, together with very high cost-effectiveness and low environmental impact. Using **prefabricated panels** to strengthen the existing envelope of a building, e.g. using TRM/TRC-based panels, integrated with thermal insulation, PCM or capillary tubes, as well as timber-based CLT or OSB panels with thermal insulation, have also shown to be promising. Prefabricated panels bring the advantage of reduced construction time, increased modularity and the potential for full integration of the structural and energy elements. A final approach for integrated retrofitting of existing walls, is the strengthening of existing openings combined with the provision of new windows. Structural window frames can stiffen the structure while improved glazing surfaces (e.g. double- or triple-glazing or other modern fenestration options) additionally provide improved thermal performance.

Replacing the external building skin of masonry-infilled RC buildings provides an alternative solution in which existing infills can be either (1) replaced by stronger and more thermally insulating bricks; or (2) replaced by deformable or decoupled infill walls. Additional thermal insulation is typically required to achieve higher levels of energy efficiency, while the use of bricks made from sustainable materials or filled with thermal insulation may help to reduce their environmental impact. It is worth noting that replacing the external envelope is a very invasive and disruptive solution that is not always applicable. Finally, only limited studies have explored **combined interventions on horizontal elements,** i.e. roof and floors even though a high potential for integration of seismic and energy interventions would exist. One example presented is the construction of an entirely new inner shell for improving the seismic performance and energy efficiency of (historic) masonry buildings, where the existing floors are replaced with CLT boards and CLT panels with thermal insulation are applied at the roof level.

Overall, despite combined retrofitting being a relatively new field of investigation, quite a number of research studies have already been published the last 5-7 years. Still, further work is required for such combined retrofitting schemes to become viable renovation solutions. For instance, only limited technologies have been tested experimentally as combined or integrated solutions, such as the experiments on TRM + thermal insulation, while in most cases the seismic performance and energy efficiency improvements have been tested separately and their integration has only been assessed through numerical models. Moreover, there is a need to investigate, test and develop more fully integrated retrofitting systems. Since the renovation of the existing building stock needs to start imminently, realistic and easy-to-adopt applications will be much more likely to have an actual impact. Combined with novel applications on existing buildings, will demonstrate the full potential of this approach. The roadmap towards a carbon-free EU definitely includes the renovation of our aged building stock and combined retrofitting techniques are of high timeliness in this respect.

References

Artino, A., G. Evola, G. Margani, and E.M. Marino, 'Seismic and Energy Retrofit of Apartment Buildings through Autoclaved Aerated Concrete (AAC) Blocks Infill Walls', *Sustainability*, Vol. 11, No. 14, July 19, 2019, p. 3939, doi:10.3390/su11143939.

Asdrubali, F., B. Ferracuti, L. Lombardi, C. Guattari, L. Evangelisti, and G. Grazieschi, 'A Review of Structural, Thermo-Physical, Acoustical, and Environmental Properties of Wooden Materials for Building Applications', *Building and Environment*, Vol. 114, March 1, 2017, pp. 307–332, doi:10.1016/j.buildenv.2016.12.033.

Bae, S., J. Oh, J. Kim, E.-R. Baek, and Y. Nam, 'Energy Performance Analysis of Textile and Capillary Tube Composite Panel System by Computational Fluid Dynamics and Real-Scale Experiments', *Energy and Buildings*, December 30, 2021, p. 111825, doi:10.1016/j.enbuild.2021.111825.

Baek, E., D.A. Pohoryles, S. Kallioras, D.A. Bournas, H. Choi, and T. Kim, 'Innovative Seismic and Energy Retrofitting of Wall Envelopes Using Prefabricated Textile-Reinforced Concrete Panels with an Embedded Capillary Tube System', *Engineering Structures*, Vol. 265, August 2022, p. 114453, doi:10.1016/j.engstruct.2022.114453.

Basiricò, T., and D. Enea, 'Seismic and Energy Retrofit of the Historic Urban Fabric of Enna (Italy)', *Sustainability*, Vol. 10, No. 4, April 2018, p. 1138, doi:10.3390/su10041138.

Belleri, A., and A. Marini, 'Does Seismic Risk Affect the Environmental Impact of Existing Buildings?', *Energy and Buildings*, Vol. 110, January 2016, pp. 149–158, doi:10.1016/j.enbuild.2015.10.048.

Bournas, D.A., *Innovative Materials for Seismic and Energy Retrofitting of the Existing EU Buildings, EUR 29184 EN*, Publications Office of the European Union, Luxembourg, 2018a, ISBN 978-92-79-81995-7, doi:10.2760/091621, *JRC109907*.

Bournas, D.A., 'Concurrent Seismic and Energy Retrofitting of RC and Masonry Building Envelopes Using Inorganic Textile-Based Composites Combined with Insulation Materials: A New Concept', *Composites Part B: Engineering*, Vol. 148, September 2018b, pp. 166–179, doi:10.1016/j.compositesb.2018.04.002.

Bru, D., A. González, F.J. Baeza, and S. Ivorra, 'Seismic Behavior of 1960's RC Buildings Exposed to Marine Environment', *Engineering Failure Analysis*, Vol. 90, 2018, pp. 324–340.

Busselli, M., D. Cassol, A. Prada, and I. Giongo, 'Timber Based Integrated Techniques to Improve Energy Efficiency and Seismic Behaviour of Existing Masonry Buildings', *Sustainability*, Vol. 13, No. 18, September 17, 2021, p. 10379, doi:10.3390/su131810379.

Calvi, G.M., L. Sousa, and C. Ruggeri, 'Energy Efficiency and Seismic Resilience: A Common Approach', in P. Gardoni and J.M. LaFave (eds.), *Multi-Hazard Approaches to Civil Infrastructure Engineering*, Springer International Publishing, Cham, 2016, pp. 165–208, ISBN 978-3-319-29711-8, doi:10.1007/978-3-319-29713-2_9.

Choi, H.-W., S.-H. Lee, H.-S. Choi, T.-H. Kim, and E.-R. Baek, 'Static Cyclic Loading Test of the Seismic and Energy Simultaneous Retrofit Panel for Existing Unreinforced Masonry Buildings', *Journal of the Korea institute for structural maintenance and inspection*, Vol. 24, No. 4, 2020, pp. 81–90, doi:10.11112/jksmi.2020.24.4.81.

Corrado, V., and I. Ballarini, 'Refurbishment Trends of the Residential Building Stock: Analysis of a Regional Pilot Case in Italy', *Energy and Buildings*, Vol. 132, 2016, pp. 91–106.

Dalla Mora, T., A. Righi, F. Peron, and P. Romagnoni, 'Functional, Energy and Seismic Retrofitting in Existing Building: An Innovative System Based on Xlam Technology', *Energy Procedia*, Vol. 82, December 1, 2015, pp. 486–492, doi:10.1016/j.egypro.2015.11.851, *70th Conference of the Italian Thermal Machines Engineering Association, ATI2015*.

Di Bucci, D., M. Dolce, D.A. Bournas, D. Combescure, D. De Gregorio, L. Galbusera, M. Leone, et al., *Science for Disaster Risk Management 2020: Acting Today, Protecting Tomorrow. EUR 30183 EN*, Edited by A. Casajus Valles, M. Marin Ferrer, K. Poljanšek, and I. Clark, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-18182-8, doi:10.2760/571085, JRC114026.

D'Urso, S., and B. Cicero, 'From the Efficiency of Nature to Parametric Design. A Holistic Approach for Sustainable Building Renovation in Seismic Regions', *Sustainability*, Vol. 11, No. 5, January 2019, p. 1227, doi:10.3390/su11051227.

Economidou, M., B. Atanasiu, C. Despret, J. Maio, I. Nolte, and O. Rapf, *Europe's Buildings under the Microscope. A Country-by-Country Review of the Energy Performance of Buildings*, Buildings Performance Institute Europe (BPIE), 2011.

European Commission, *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, Improving Lives*, Brussels, October 14, 2020.

European Commission, *The European Green Deal - Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions.*, European Commission, Brussels, November 12, 2019.

European Parliament and Council of the European Union, Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency (Text with EEA Relevance), *156*, Vol. OJ L, Vol. OJ L, 19.6.2018.

eurostat, 'Census 2011', 2011. https://ec.europa.eu/CensusHub2/.

eurostat, 'Inability to Keep Home Adequately Warm - EU-SILC Survey [Ilc_mdes01]', 2019. https://ec.europa.eu/eurostat/databrowser/view/sdg_07_60/default/table?lang=en.

Facconi, L., S.S. Lucchini, F. Minelli, B. Grassi, M. Pilotelli, and G.A. Plizzari, 'Innovative Method for Seismic and Energy Retrofitting of Masonry Buildings', *Sustainability*, Vol. 13, No. 11, January 2021, p. 6350, doi:10.3390/su13116350.

Ferrante, A., G. Mochi, G. Predari, L. Badini, A. Fotopoulou, R. Gulli, and G. Semprini, 'A European Project for Safer and Energy Efficient Buildings: Pro-GET-OnE (Proactive Synergy of InteGrated Efficient Technologies on Buildings' Envelopes)', *Sustainability*, Vol. 10, No. 3, March 2018, p. 812, doi:10.3390/su10030812.

Foti, D., F. Ruggiero, M.F. Sabbà, and M. Lerna, 'A Dissipating Frames for Seismic Retrofitting and Building Energy-Efficiency', *Infrastructures*, Vol. 5, No. 9, September 2020, p. 74, doi:10.3390/infrastructures5090074.

Gattesco, N., and L. Macorini, 'High Reversibility Technique for In-Plane Stiffening of Wooden Floors', in E. Fodde (ed.), *Structural Analysis of Historic Construction: Preserving Safety and Significance*, CRC Press, 2008, pp. 1035–1042, ISBN 978-0-415-46872-5, doi:10.1201/9781439828229.ch118.

Giaretton, M., D. Dizhur, E. Garbin, J.M. Ingham, and F. da Porto, 'In-Plane Strengthening of Clay Brick and Block Masonry Walls Using Textile-Reinforced Mortar', *Journal of Composites for Construction*, Vol. 22, No. 5, October 2018, p. 04018028, doi:10.1061/(ASCE)CC.1943-5614.0000866.

Giuriani, E.P., A. Marini, and M. Preti, 'Thin-Folded Shell for the Renewal of Existing Wooden Roofs', *International Journal of Architectural Heritage*, Vol. 10, No. 6, August 17, 2016, pp. 797–816, doi:10.1080/15583058.2015.1075626.

Gkournelos, P.D., T.C. Triantafillou, and D.A. Bournas, 'Integrated Structural and Energy Retrofitting of Masonry Walls: Effect of In-Plane Damage on the Out-of-Plane Response', *Journal of Composites for Construction*, Vol. 24, No. 5, October 1, 2020, p. 04020049, doi:10.1061/(ASCE)CC.1943-5614.0001066.

Gkournelos, P.D., D.A. Bournas, and T.C. Triantafillou, 'Combined Seismic and Energy Upgrading of Existing Reinforced Concrete Buildings Using TRM Jacketing and Thermal Insulation', *Earthquakes and Structures*, Vol. 16, No. 5, May 25, 2019, pp. 625–639, doi:10.12989/EAS.2019.16.5.625.

Kallioras, S., D.A. Pohoryles, D.A. Bournas, F.J. Molina, and P. Pegon, 'Pseudodynamic Tests on a Full-Scale Reinforced Concrete Building with Masonry Infills: Preliminary Results on the Global Response', *Proc., 17th European Conference on Earthquake Engineering*, Bucharest, Romania, 2022.

Kant, K., A. Shukla, and A. Sharma, 'Heat Transfer Studies of Building Brick Containing Phase Change Materials', *Solar Energy*, Vol. 155, October 1, 2017, pp. 1233–1242, doi:10.1016/j.solener.2017.07.072.

Karlos, K., A. Tsantilis, and T. Triantafillou, 'Integrated Seismic and Energy Retrofitting System for Masonry Walls Using Textile-Reinforced Mortars Combined with Thermal Insulation: Experimental, Analytical, and Numerical Study', *Journal of Composites Science*, Vol. 4, No. 4, December 2020, p. 189, doi:10.3390/jcs4040189.

Köliö, A., T.A. Pakkala, J. Lahdensivu, and M. Kiviste, 'Durability Demands Related to Carbonation Induced Corrosion for Finnish Concrete Buildings in Changing Climate', *Engineering Structures*, Vol. 62, 2014, pp. 42–52.

Labò, S., C. Passoni, A. Marini, and A. Belleri, 'Design of Diagrid Exoskeletons for the Retrofit of Existing RC Buildings', *Engineering Structures*, Vol. 220, October 1, 2020a, p. 110899, doi:10.1016/j.engstruct.2020.110899.

Labò, S., C. Passoni, A. Marini, A. Belleri, G. Camata, P. Riva, and E. Spacone, 'Diagrid Solutions for a Sustainable Seismic, Energy, and Architectural Upgrade of European RC Buildings', *Proceedings of the XII International Conference on Structural Repair and Rehabilitation, Porto, Portugal*, 2016, pp. 26–29.

Labò, S., C. Passoni, J. Zanni, A. Marini, A. Belleri, and P. Riva, 'Retrofit of Existing RC Buildings with Diagrids Adopting a Holistic-Sustainable Design Framework', in O. Iuorio and P. Negro (eds.), *A Roadmap for a SUstainable Integrated REtrofit of CONcrete Buildings*, Publications Office of the European Union, Luxembourg, 2020b, pp. 43–46, ISBN 978-92-76-23864-5, Vol. JRC119041 of.

Manfredi, V., A. Masi, G. Ventura, L. Chiauzzi, A. Digrisolo, and G. Santarsiero, 'Rafforzamento sismico degli edifici esistenti in c.a. una soluzione innovativa per interventi integrati e sostenibili', *Structural*, Vol. 215, February 2018, doi:10.12917/STRU215.03.

Manfredi, V., and A. Masi, 'Seismic Strengthening and Energy Efficiency: Towards an Integrated Approach for the Rehabilitation of Existing RC Buildings', *Buildings*, Vol. 8, No. 3, March 1, 2018, p. 36, doi:10.3390/buildings8030036.

Manfredi, V., G. Santarsiero, A. Masi, and G. Ventura, 'The High-Performance Dissipating Frame (HPDF) System for the Seismic Strengthening of RC Existing Buildings', *Sustainability*, Vol. 13, No. 4, January 2021, p. 1864, doi:10.3390/su13041864.

Margani, G., G. Evola, C. Tardo, and E.M. Marino, 'Energy, Seismic, and Architectural Renovation of RC Framed Buildings with Prefabricated Timber Panels', *Sustainability*, Vol. 12, No. 12, June 13, 2020, p. 4845, doi:10.3390/su12124845.

Marini, A., A. Belleri, F. Feroldi, C. Passoni, M. Preti, P. Riva, E. Giuriani, and G. Plizzari, 'Coupling Energy Refurbishment with Structural Strengthening in Retrofit Interventions', in A. Caverzan, M. Lamperti Tornaghi, and P. Negro (eds.), *Proceedings of SAFESUST Workshop - A Roadmap for the Improvement of Earthquake Resistance and Eco-Efficiency of Existing Buildings and Cities*, Publications Office of the European Union, Luxembourg, 2016, pp. 26–27, ISBN 978-92-79-62618-0, Vol. JRC103289 of.

Marini, A., C. Passoni, A. Belleri, F. Feroldi, M. Preti, G. Metelli, P. Riva, E. Giuriani, and G. Plizzari, 'Combining Seismic Retrofit with Energy Refurbishment for the Sustainable Renovation of RC Buildings: A Proof of Concept', *European Journal of Environmental and Civil Engineering*, September 3, 2017, pp. 1–21, doi:10.1080/19648189.2017.1363665.

Marinković, M., and C. Butenweg, 'Innovative Decoupling System for the Seismic Protection of Masonry Infill Walls in Reinforced Concrete Frames', *Engineering Structures*, Vol. 197, October 15, 2019, p. 109435, doi:10.1016/j.engstruct.2019.109435.

Martelli, L., L. Restuccia, and G.A. Ferro, 'The Exoskeleton: A Solution for Seismic Retrofitting of Existing Buildings', *Procedia Structural Integrity*, Vol. 25, 2020, pp. 294–304, doi:10.1016/j.prostr.2020.04.034.

Masi, A., G. Santarsiero, and G. Ventura, 'Strategie per la riduzione del rischio sismico applicate agli edifici scolastici: un caso studio', *XVII Convegno ANIDIS L'ingegneria Sismica in Italia*, Pistoia, 2017, pp. 17–21.

Misawa, Y., K. Azuma, W. Cho, S. Iwamoto, and M. Iwata, 'Simulation Study on Energy Conservation Performance for Integrated External Louver Facades', *Journal of Facade Design and Engineering*, Vol. 3, No. 3–4, June 23, 2016, pp. 237–252, doi:10.3233/FDE-160043.

Morandi, P., R.R. Milanesi, and G. Magenes, 'Innovative Solution for Seismic-Resistant Masonry Infills with Sliding Joints: In-Plane Experimental Performance', *Engineering Structures*, Vol. 176, December 1, 2018, pp. 719–733, doi:10.1016/j.engstruct.2018.09.018.

Nocera, F., A. Gagliano, and M. Detommaso, 'Energy Performance of Cross-Laminated Timber Panel (X-Lam) Buildings: A Case Study', *Mathematical Modelling of Engineering Problems*, Vol. 5, No. 3, September 30, 2018, pp. 175–182, doi:10.18280/mmep.050307.

Oña Vera, Mónica.Y., G. Metelli, J.A.O. Barros, and G.A. Plizzari, 'Effectiveness of a Steel Ring-Frame for the Seismic Strengthening of Masonry Walls with New Openings', *Engineering Structures*, Vol. 226, January 1, 2021, p. 111341, doi:10.1016/j.engstruct.2020.111341.

Palermo, V., G. Tsionis, and M.L. Sousa, *Building Stock Inventory to Assess Seismic Vulnerability across Europe*, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-86707-1, Vol. EUR 29257 EN of.

Pertile, V., L. De Stefani, and R. Scotta, 'Development and Characterization of a System for the Seismic and Energy Retrofit of Existing Buildings', *Procedia Structural Integrity*, Vol. 11, Elsevier, Florence, Italy, 2018, pp. 347–354, doi:10.1016/j.prostr.2018.11.045.

Pertile, V., L. De Stefani, and R. Scotta, 'Thin Insulated Concrete Panels for Integrated Retrofit of Buildings', *Journal of Building Engineering*, under review 2021.

Pertile, V., A. Stella, L. De Stefani, and R. Scotta, 'Experimental Tests on Full-Scale Specimens for the Characterization of an Integrated Retrofitting System for Existing Buildings', *Proc. 18th ANIDIS Conference*, ANIDIS, Ascoli Piceno (Italy), 2019.

Pohoryles, D.A., and D.A. Bournas, 'A Unified Macro-Modelling Approach for Masonry-Infilled RC Frames Strengthened with Composite Materials', *Engineering Structures*, Vol. 223, November 15, 2020a, p. 111161, doi:10.1016/j.engstruct.2020.111161.

Pohoryles, D.A., and D.A. Bournas, *IRESIST+ Innovative Seismic and Energy Retrofitting of the Existing Building Stock*, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-29686-7, doi:10.2760/496388, Vol. JRC123638 of.

Pohoryles, D.A., and D.A. Bournas, 'Seismic Retrofit of Infilled RC Frames with Textile Reinforced Mortars: State-of-the-Art Review and Analytical Modelling', *Composites Part B: Engineering*, Vol. 183, February 15, 2020b, p. 107702, doi:10.1016/j.compositesb.2019.107702.

Pohoryles, D.A., D.A. Bournas, F. da Porto, G. Santarsiero, T. Triantafillou, D.V. Oliveira, and B.P. Jelle, *Technologies for the Combined Seismic and Energy Upgrading of Existing Buildings*, Publications Office of the European Union, Luxembourg, 2022a, ISBN 978-92-76-49257-3, doi:10.2760/86567, *JRC128458*.

Pohoryles, D.A., C. Maduta, D.A. Bournas, and L.A. Kouris, 'Energy Performance of Existing Residential Buildings in Europe: A Novel Approach Combining Energy with Seismic Retrofitting', *Energy and Buildings*, Vol. 223, September 15, 2020, p. 110024, doi:10.1016/j.enbuild.2020.110024.

Pohoryles, D.A., D.A. Bournas, F. Da Porto, A. Caprino, G. Santarsiero, and T. Triantafillou, 'Integrated Seismic and Energy Retrofitting of Existing Buildings: A State-of-the-Art Review', *Journal of Building Engineering*, Vol. 61, December 2022b, p. 105274, doi:10.1016/j.jobe.2022.105274.

da Porto, F., M. Donà, N. Verlato, and G. Guidi, 'Experimental Testing and Numerical Modeling of Robust Unreinforced and Reinforced Clay Masonry Infill Walls, With and Without Openings', *Frontiers in Built Environment*, Vol. 0, 2020, doi:10.3389/fbuil.2020.591985.

Pozza, L., A. Degli Esposti, A. Bonoli, D. Talledo, L. Barbaresi, G. Semprini, and M. Savoia, 'Multidisciplinary Performance Assessment of an Eco-Sustainable RC-Framed Skin for the Integrated Upgrading of Existing Buildings', *Sustainability*, Vol. 13, No. 16, January 2021, p. 9225, doi:10.3390/su13169225.

Proença, J.M., A.S. Gago, and A.V. Boas, 'Structural Window Frame for In-Plane Seismic Strengthening of Masonry Wall Buildings', *International Journal of Architectural Heritage*, Vol. 13, No. 1, January 2, 2019, pp. 98–113, doi:10.1080/15583058.2018.1497234.

Salvalai, G., M.M. Sesana, and G. Iannaccone, 'Deep Renovation of Multi-Storey Multi-Owner Existing Residential Buildings: A Pilot Case Study in Italy', *Energy and Buildings*, Vol. 148, 2017, pp. 23–36.

Santarsiero, G., A. Masi, V. Manfredi, and G. Ventura, 'Requalification of RC Frame Apartment Buildings: Comparison of Seismic Retrofit Solutions Based on a Multi-Criteria Approach', *Sustainability*, Vol. 13, No. 17, September 6, 2021, p. 9962, doi:10.3390/su13179962.

Saxena, R., D. Rakshit, and S.C. Kaushik, 'Experimental Assessment of Phase Change Material (PCM) Embedded Bricks for Passive Conditioning in Buildings', *Renewable Energy*, Vol. 149, April 1, 2020, pp. 587–599, doi:10.1016/j.renene.2019.12.081.

Smiroldo, F., I. Paviani, I. Giongo, S. Zanon, R. Albatici, and M. Piazza, 'An Integrated Approach to Improve Seismic and Energetic Behaviour of RC Framed Buildings Using Timber Panels', *Sustainability*, Vol. 13, No. 20, October 13, 2021, p. 11304, doi:10.3390/su132011304.

de Sousa, C., J.A.O. Barros, J. Ramôa Correia, and T.D.S. Valente, 'Development of Sandwich Panels for Multi-Functional Strengthening of RC Buildings: Characterization of Constituent Materials and Shear Interaction of Panel Assemblies', *Construction and Building Materials*, Vol. 267, January 18, 2021, p. 120849, doi:10.1016/j.conbuildmat.2020.120849.

Stazi, F., M. Serpilli, G. Maracchini, and A. Pavone, 'An Experimental and Numerical Study on CLT Panels Used as Infill Shear Walls for RC Buildings Retrofit', *Construction and Building Materials*, Vol. 211, June 30, 2019, pp. 605–616, doi:10.1016/j.conbuildmat.2019.03.196.

Takeuchi, T., K. Yasuda, and M. Iwata, 'Seismic Retrofitting Using Energy Dissipation Façades', *Improving the Seismic Performance of Existing Buildings and Other Structures*, American Society of Civil Engineers, San Francisco, California, United States, 2009, pp. 1000–1009, ISBN 978-0-7844-1084-4, doi:10.1061/41084(364)91.

Takeuchi, T., K. Koyano, and M. Iwata, 'Studies on Integrated Facade Engineering: Analyses on Existing Facades', *Journal of Environmental Engineering (Transactions of AIJ)*, Vol. 70, No. 592, 2005, pp. 97–104, doi:10.3130/aije.70.97_2.

Takeuchi, T., K. Yasuda, and M. Iwata, 'Studies on Integrated Building Façade Engineering with High-Performance Structural Elements', *IABSE Symposium Report*, Vol. 92, International Association for Bridge and Structural Engineering, 2006, pp. 33–40.

Triantafillou, T.C., K. Karlos, P. Kapsalis, and L. Georgiou, 'Innovative Structural and Energy Retrofitting System for Masonry Walls Using Textile Reinforced Mortars Combined with Thermal Insulation: In-Plane Mechanical Behavior', *Journal of Composites for Construction*, Vol. 22, No. 5, October 1, 2018, p. 04018029, doi:10.1061/(ASCE)CC.1943-5614.0000869.

Triantafillou, T.C., K. Karlos, K. Kefalou, and E. Argyropoulou, 'An Innovative Structural and Energy Retrofitting System for URM Walls Using Textile Reinforced Mortars Combined with Thermal Insulation: Mechanical and Fire Behavior', *Construction and Building Materials*, Vol. 133, February 2017, pp. 1–13, doi:10.1016/j.conbuildmat.2016.12.032.

Tsantilis, A.V., and T.C. Triantafillou, 'Innovative Seismic Isolation of Masonry Infills in Steel Frames Using Cellular Materials at the Frame-Infill Interface', *Journal of Earthquake Engineering*, Vol. 0, No. 0, June 4, 2018a, pp. 1–18, doi:10.1080/13632469.2018.1478347.

Tsantilis, A.V., and T.C. Triantafillou, 'Innovative Seismic Isolation of Masonry Infills Using Cellular Materials at the Interface with the Surrounding RC Frames', *Engineering Structures*, Vol. 155, January 15, 2018b, pp. 279–297, doi:10.1016/j.engstruct.2017.11.025.

Vailati, M., G. Monti, and G. Di Gangi, 'Earthquake-Safe and Energy-Efficient Infill Panels for Modern Buildings', in R. Rupakhety and S. Ólafsson (eds.), *Earthquake Engineering and Structural Dynamics in Memory of Ragnar Sigbjörnsson: Selected Topics*, Springer International Publishing, Cham, 2018, pp. 233–261, ISBN 978-3-319-62099-2, doi:10.1007/978-3-319-62099-2_12, *Geotechnical, Geological and Earthquake Engineering*.

Valluzzi, M.R., E. Saler, A. Vignato, M. Salvalaggio, G. Croatto, G. Dorigatti, and U. Turrini, 'Nested Buildings: An Innovative Strategy for the Integrated Seismic and Energy Retrofit of Existing Masonry Buildings with CLT Panels', *Sustainability*, Vol. 13, No. 3, January 2021, p. 1188, doi:10.3390/su13031188.

Verlato, N., G. Guidi, F. da Porto, and C. Modena, 'Innovative Systems for Masonry Infill Walls Based on the Use of Deformable Joints: Combined in-Plane/out-of-Plane Tests', *Brick and Block Masonry*, CRC Press, 2016, ISBN 978-1-315-37496-3.

Vintzileou, E., C.E. Adami, and V. Palieraki, 'In-Plane and out-of-Plane Response of a Masonry Infill Divided into Smaller Wallettes', *Brick and Block Masonry*, CRC Press, 2016, ISBN 978-1-315-37496-3.

Wernery, J., A. Ben-Ishai, B. Binder, and S. Brunner, 'Aerobrick — An Aerogel-Filled Insulating Brick', *Energy Procedia*, Vol. 134, October 1, 2017, pp. 490–498, doi:10.1016/j.egypro.2017.09.607, *Sustainability in Energy and Buildings 2017: Proceedings of the Ninth KES International Conference, Chania, Greece, 5-7 July 2017*.

Žarnić, R., V. Rajčić, and M. Kržan, 'Response of Laminated Glass-CLT Structural Components to Reverse-Cyclic Lateral Loading', *Construction and Building Materials*, Vol. 235, February 28, 2020, p. 117509, doi:10.1016/j.conbuildmat.2019.117509.

List of abbreviations and definitions

AAC	Autoclaved Aerated Concrete
BIPV	Building Integrated Photovoltaics
CLT	Cross-laminated Timber
ECC	Engineered Cementitious Composites
EPS	Expanded Polystyrene
EU	European Union
FRP	Fibre Reinforced Polymer
HVAC	Heating, ventilation, and air conditioning
JRC	Joint Research Center
MS	Member State
OSB	Oriented Strand Board
PCM	Phase Change Material
PUR	Polyurethane
RC	Reinforced Concrete
TCP	Textile and Capillary tube Composite Panel
TRM	Textile Reinforced Mortar
URM	Unreinforced Masonry
XPS	Extruded Polystyrene

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