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

Technologies for the combined seismic and energy upgrading of existing buildings

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REEBUILD

Integrated Techniques for the
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Foreword

Our buildings are ageing, posing an urgent need for renovation to align with the goals of multidimensional European and international policies. The built-up area in Europe covers 25 billion square meters, 10 billion of which were constructed before 1960 and 20 billion before 1990. 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 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 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), besides reducing greenhouse gas emissions, measures related to seismic risk and fire safety are encouraged for planning long-term renovation strategies. The implementation of clean and circular economy principles for the construction sector to achieve a climate-neutral society by 2050 are stressed in the new Circular Economy Action Plan (COM (2020)98) which also addresses the revision of the Construction Products Regulation (Regulation (EU) 305/2011). The new idea for a holistic approach to the renovation of buildings is in line with the Union Civil Protection Mechanism (Decision (EU) 2019/420), with respect to disaster prevention measures and the integration of risk reduction and cohesion policies. Likewise, the Action Plan on the Sendai Framework (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 (SWD 2018/491) emphasises the need to safeguard cultural heritage against natural disasters and climate change, and relevant measures are encouraged when planning long-term renovation strategies and national disaster risk reduction strategies. The above policies and initiatives contribute to the implementation of the 2030 Agenda for Sustainable Development (Resolution 2015/A/Res/70/1) and the Sustainable Development Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable".

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.

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Abstract

To achieve the ambitious target of climate neutrality of the EU set out within the EU Green Deal, a reduction of energy use in the highly energy consuming building sector is critical. To achieve this, the renovation of existing buildings has been given a key role, starting with the Renovation Wave initiative. In fact, a large proportion of existing buildings in the EU are characterised by a high energy consumption for heating and cooling, often caused by poor or non-existent thermal insulation, as well as outdated heating and cooling systems. It is hence critical to improve their energy-efficiency through renovation to reduce the significant impact of the built environment on the total EU energy household and associated greenhouse gas emissions. Additionally, in Europe's seismic regions, earthquakes can cause significant human and economic losses, with a large impact on society. Recent seismic events have highlighted the vulnerability of older buildings with structural deficiencies that are in dire need for seismic retrofitting. It appears that a large proportion of the EU building stock requires renovation from both structural and energy perspectives. While these are typically addressed separately, recent scientific developments highlight better cost-effectiveness, safety and efficiency can be achieved when taking an integrated approach to building renovation. This report presents materials and technologies being developed and presented in the scientific literature, ranging from integrated exoskeleton solutions, over strengthening and insulation solutions for the existing building envelope or their replacement with better materials, to integrated interventions on horizontal elements like roof and floor slabs. While the field of integrated structural and energy retrofitting is still in its infancy, valuable results and insights have already been obtained. Proposed technologies are presented and critically analysed in terms of their relative effectiveness, invasiveness, impact on the building use disruption, costs, as well as their impact on the environment. Further experimental research and validation of fully integrated retrofitting systems, which can be applied simultaneously at a low cost, is still needed. Together with pilot applications on existing buildings, this will demonstrate the full potential of integrated renovation approaches. The renovation of our ageing building stock will be a key element of the path towards a carbon-neutral EU and combined retrofitting techniques provide a cost-effective solution in seismic region, with a potential for accelerating renovation rates.

1 Introduction

Within the EU, buildings are responsible for 40% of the total consumption of energy and 36% of greenhouse gas emissions (European Commission, 2019). These values are mainly attributed to their poor energy performance, as most of them were erected more than 30 years ago when no strict energy regulations were enforced (Economidou et al., 2011). To tackle the issue of energy efficiency in the built environment sector, the European Green Deal (Communication 2019/640) emphasises the need for the EU and its Member States to engage in a "**renovation wave**" of public and private buildings (European Commission, 2020). To support its implementation, the Commission recently announced the New European Bauhaus initiative (STATEMENT/20/1902), intending to integrate aesthetics, sustainability and inclusion within the built environment.

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). 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 proven in recent past events that have taken place within the European continent, e.g.: Athens 1999, L' Aquila 2009, Emilia 2012, Central Italy 2016-2017 (Di Bucci et al., 2021). To increase **resilience**, investments in disaster risk reduction are encouraged within the Action Plan on the Sendai network (SWD 2016/205), which promotes "Build Back Better" principles for the built environment (European Commission, 2016).

Earthquakes are however not the only danger that existing structures have to stand up against. As more and more buildings approach the end of their conventional service life, durability related damage types emerge as well. For instance, the excessive corrosion of steel reinforcement or structural steel members can greatly decrease the capacity of structural elements and even result in their collapse (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.

A possible avenue to reduce the energy consumption related to buildings and to mitigate the seismic risk of structurally deficient ones is their complete replacement. Clearly, such a drastic measure would have a severe impact on society, the existing urban fabric and would not be financially feasible, given that 80% of buildings were built before 1990. Moreover, demolition and rebuilding are not sustainable solutions, as they require the use of large quantities of new materials and result in significant waste. In the context of the New Circular Economy Action Plan (Communication 2020/98), instead, approaches compatible with **life cycle thinking** should be adopted, i.e. giving preference to the lifetime-extension of existing buildings through maintenance, repair and upgrading.

Until recently, renovation efforts and policies were mainly directed to the energy upgrading of buildings alone, without taking into account their structural integrity. From a financial point of view, benefits from an energy upgrading are immediately evident, through the reduced energy costs for heating/cooling. Therefore, the initial investment starts paying itself back immediately after the renovation works have been completed. However, if the structural integrity of the retrofitted building is not guaranteed, that same investment could be completely lost, in case excessive structural damage occurs. This could take place for example during a large intensity earthquake or even due to partial collapses related to poor durability, as explained earlier. Similarly, seismic retrofitting interventions alone could compromise thermal comfort if a building's energy efficiency is not considered.

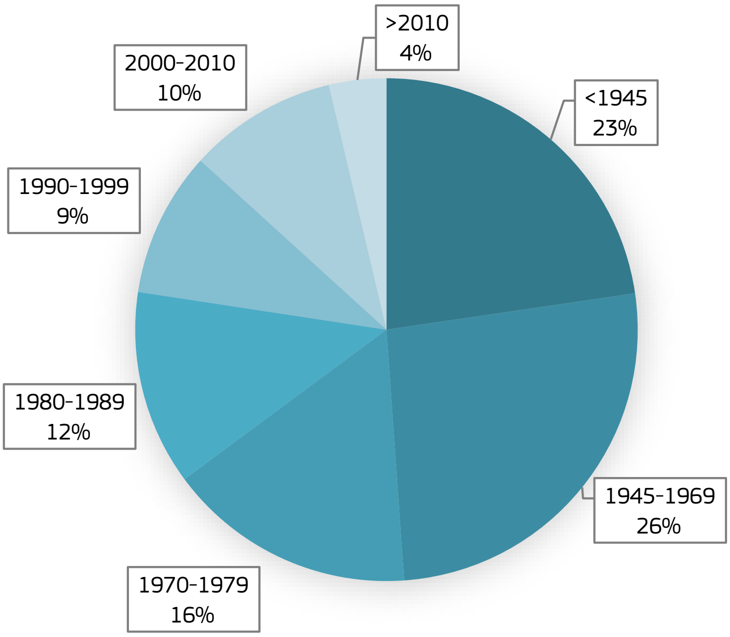
Given that there is a large proportion of buildings in Europe that have inadequacies in terms of structural and thermal performance, the scale of refurbishment works needed is significant. This comes with a significant financial burden in terms of the required investments into building renovation. To ensure the longevity of energy upgrading investments, a holistic approach to renovation is instrumental. The 2018 amendment to the Energy Performance of Buildings Directive (European Parliament and Council of the European Union, 2018) hence encourages the Member States to take into consideration measures related to fire safety and seismic risks, which affect the lifetime of buildings, for planning long-term renovation strategies.

In the scientific literature, the topic of integrated retrofitting has gained traction only over the last few years. This report aims to present an overview of the developments in retrofit materials and technologies conceived for the seismic safety and energy performance upgrading of existing buildings. It provides comparisons among their effectiveness, costs, disruptiveness and invasiveness, as well as taking into account their environmental impact. First, a brief overview of the characteristics of the EU building stock and the typical structural and energy efficiency deficiencies of existing buildings is presented in **Section 2**. In **Section 3**, the concepts and materials for seismic and energy retrofitting are introduced to give the reader a general background. Concepts for combining retrofitting technologies based on their scale, invasiveness and general compatibility are introduced in **Section 4**, and then a detailed state-of-the-art review of integrated seismic-plus-energy retrofitting methods is presented. **Section 5** consists of an analysis and comparison of the previously presented technology options. In particular, the involved costs, environmental impact of the materials, occupancy disruption and down-time due to the interventions are compared. Finally, potential economic benefits, as well as the technical and financial barriers of the implementation of integrated retrofitting are discussed, followed by a brief overview of incentives and regulatory frameworks that may help to overcome said barriers.

2 The European building stock

The majority of buildings in the EU are residential and have been built during the post-World War II period 1945-1969, according to the public data provided by the EU Buildings Observatory. **Figure 1** shows the percentages of the buildings according to their period of construction; important conclusions drawn out of it are as follows:

Figure 1. Split of buildings in the EU by construction time.



Source: EU Buildings Observatory.

— Almost half of the building stock (49%) is older than 50 years old. This means that it has already completed its conventional life and is by definition in need of retrofitting or replacement, due to durability related issues.

— More than three quarters (77%) have been built before 1990, which is before the first edition of modern seismic codes (e.g. Eurocodes) were published. Therefore, this part of buildings, if checked against the current standards, would be found most probably seismically deficient and thus in need of strengthening.

— Most buildings have also been constructed without accounting for their energy efficiency, especially in southern countries where the heating needs are less. The application of energy standards varies extensively, among countries; in Greece for example, the Code for Energy Efficiency of Buildings came into force in 2010.

As a result of the conclusions stated above, it is evident that a large portion of the existing buildings is both energy and seismically inefficient. The following subsections outline the major deficiencies encountered in existing structures from the structural safety and energy efficiency point of view.

2.1 Structural deficiencies

Most structural deficiencies found in older buildings stem from the fact that they have been built a long time ago using lower-quality materials and designed according to outdated codes which have been updated several times since then. In European countries affected by earthquakes, seismic standards have changed considerably during the last 50 years, typically following major earthquake events, with adaptations both in terms of the prescribed loads and of detailing measures (Palermo et al., 2018). Therefore, the bearing capacity of various structural elements is expected to have degraded since their construction due to physical phenomena (e.g. corrosion of reinforcement) or conditions of past overloading (e.g. earthquakes, winds, vertical loads not accounted for during design).

The two main categories of buildings in the seismic-prone regions of Europe are reinforced concrete (RC) and masonry structures (Tsionis, 2015). Seismic deficiencies of buildings have been highlighted by earthquakes in the Mediterranean area, where the seismic hazard is higher than in other EU zones (e.g.: Ricci et al., 2011; De Luca et al., 2014). Some of the most frequent issues of existing RC buildings are summarised below:

— Lower quality materials were used. In the past, concrete had significantly lower strength and quality control and lower quality steel was used in the construction. Additionally, with age corrosion of RC and steel columns is commonly found in many old buildings and bridges, especially when situated near corrosive (e.g. coastal) environments (Karapetrou et al., 2017; Bru et al., 2018).

— Smaller sections with significantly less reinforcement were selected due to the less strict standards. Therefore, many elements are under-designed and vulnerable to excessive loadings.

— No capacity design was employed neither locally (to force flexure response), or globally (to enforce strong-column-weak-beam mechanisms). Brittle mechanisms, e.g. joint shear failure or soft-storey collapses are frequently observed for older structures during earthquakes (e.g. **Figure 2**b).

— Short columns are commonly found in many old buildings, mainly due to the poorly detailed infills and staircases. When the structure is loaded laterally, these elements attract much higher loads than those designed against and fail in shear.

— External infill walls in RC buildings, although not considered to be structural elements, have significant interaction with the structure during seismic events, and can present a high vulnerability in case of seismic events. Infills, as shown by recent events, are particularly damage-prone to in and out-of-plane mechanisms, but also due to their combination (e.g. **Figure 2**a). Local failure of the infill panels can lead to a sudden drop in capacity and hence cause global brittle failure of the structure. On the other hand, irregular plan or elevation distribution of the infill walls may lead to torsional effects or soft-storey effects.

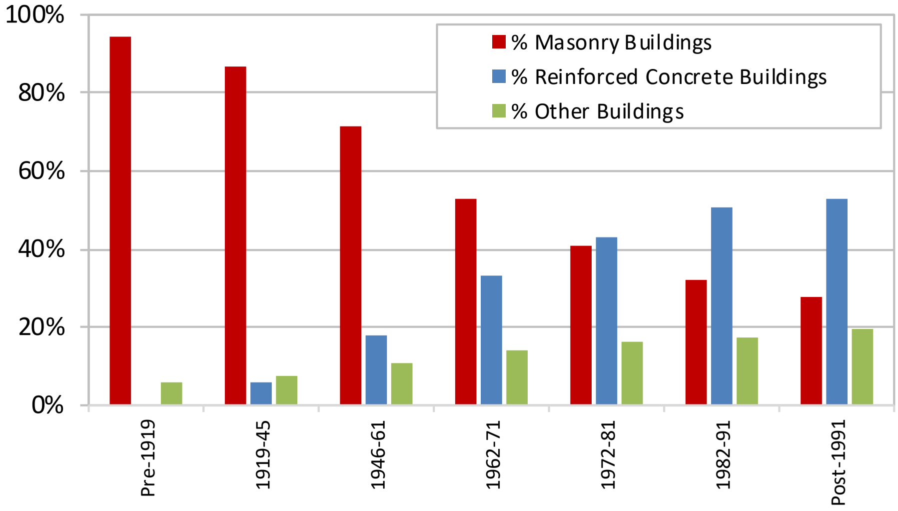
Figure 2. Seismic damage after the 2009 L'Aquila earthquake (a) Damaged infills in RC frame structure; (b) Soft-storey failure.

(a) (b)

Source: Daniel Pohoryles

It is important to consider that a large amount of the existing European building stock consists of masonry buildings. While their construction is less common nowadays, they comprise the majority of the older structures built in absence of seismic codes, including heritage and cultural buildings. For instance, **Figure 3** shows the evolution of construction materials for residential buildings in Italy. As can be seen, about 86% of masonry buildings had already been constructed by 1981, the year following the destructive Irpinia-Basilicata earthquake (1980), which brought on a major reclassification of seismic hazard zones (DM n. 515/1981). Moreover, the first code for the seismic design of masonry buildings was issued only in 1987 (DM 20/11/1987).

Figure 3. Trend of buildings in Italy during the 20th century.



Source: ISTAT 2001

The main seismic vulnerabilities are related to the poor quality of masonry walls and/or lacks in the whole structural arrangement (Borri et al., 2015). Deficiencies related to the masonry quality are:

— Poor quality of masonry due to low strength of stone/brick elements and mortar;

— Excessive mortar bed thickness and irregular configuration.

— Irregular wall arrangement due to dimension of stone/brick elements;

— Weak connection among different leafs and presence of an infill core;

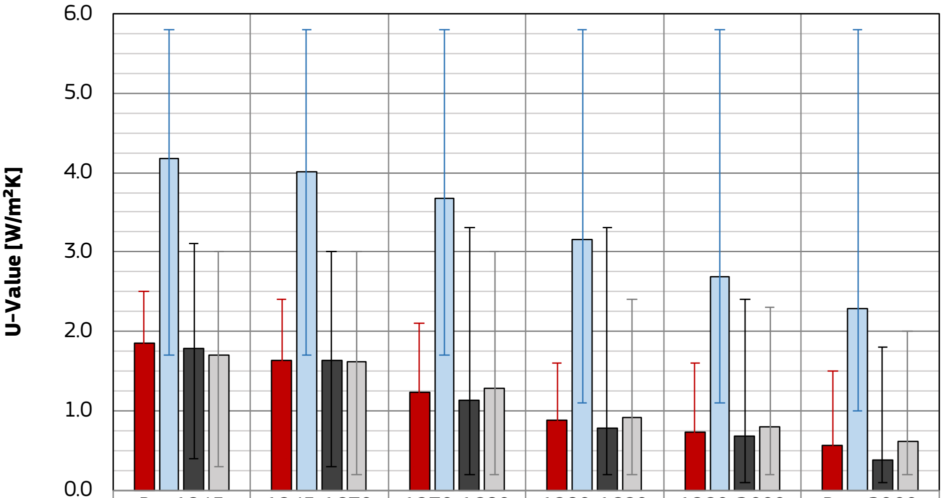
Vulnerability of masonry buildings has been highlighted by recent earthquakes (e.g.: Indirli et al., 2013). Observed failure mechanisms include in-plane shear damage to URM walls, as well as their out-of-plane failures. Additionally, deficiencies related to the structural arrangement are mainly dependent on poor connection between walls at corners, weak connection between slab and walls, or the presence of flexible diaphragms preventing a box behaviour under seismic loads.

2.2 Energy deficiencies

Deficiencies in existing buildings in terms of energy efficiency are mainly due to the absence of regulations at their time of construction, as well as the deterioration of materials with time. The first energy regulations in the EU appeared in the Scandinavian countries due to their colder weather, back in the late 1950s (Gkournelos et al., 2019). Other regions followed at the start of the 1970s, as a result of the oil supply crisis and were increased further after the Kyoto Protocol, aiming to reduce the CO_2 emissions. Later, other countries have introduced standards, regularly updated over time, especially to match European directives. Nowadays, new buildings, constructed within the EU, are required to abide by a set of energy efficiency regulations, so that all contemporary structures have a minimum acceptable energy performance.

The adoption of those energy standards, however, did not take place in many countries up until recently. For example, in Italy, the first regulation related energy efficiency of buildings was enforced in 1991 (Camera dei deputati and Senato della Repubblica, 1991). As a result, there is a large portion of buildings that are energy inefficient due to minimal insulation measures or even none at all. The lack of energy standards is also clearly visible when looking at the evolution of thermal transmittance (U-value) of different building elements (walls, windows, roofs and floors) for residential buildings in the EU (**Figure 4**). As can be seen, older structures have significantly higher thermal transmittance values than modern ones, leading to higher energy consumption and significantly worse thermal comfort.

Figure 4. Summary U-values of different building elements residential building across time: Weighted average, minimum and maximum values within EU-27 (weighted averages indicated in the table).



	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	1.84	1.63	1.23	0.88	0.74	0.56
Window	4.18	4.01	3.67	3.15	2.68	2.29
Roof	1.79	1.63	1.13	0.79	0.69	0.38
Floor	1.71	1.62	1.28	0.91	0.80	0.62

Wall Window Roof Floor

Source: Produced based on data from the INSPiRe project (iNSPiRe, 2014).

The main energy-related deficiencies observed in older structures are outlined below.

— Inadequate or complete lack of insulation. This involves both vertical (walls) and horizontal (roofs) elements of the building envelope. Even when some insulation was used, the installation was not receiving the required attention and thermal bridges were a usual phenomenon. As a result, heating and cooling such a building requires large amounts of energy.

— Inefficient fenestration surfaces. In the past, windows and doors used to have much lower thermal resistance, providing that way an easy path for heat to escape. Single pane windows and low-quality frames were used, as opposed to multi-pane, airtight frames found in most contemporary structures.

— Inefficient and aged mechanical heating, ventilation and air conditioning (HVAC) equipment. Heating was provided mainly with oil or gas furnaces while cooling with air-conditioning systems and heat pumps. As expected, older equipment has lower efficiency, compared to contemporary systems. Moreover, nowadays many solutions involving solar panels are also available in the market, which can cover part of the electricity needs and domestic hot water.

Addressing the above issues of older buildings via suitable energy retrofitting solutions seems to be very promising in reducing the energy needs of the current building stock. That is why many states are already offering subsidies to citizens to assist them with the renovation of their dwellings. An energy upgrade of a given structure is an investment that can be achieved at reasonable costs and will have an immediate effect on its consumption and thus its energy bills. Nonetheless, as stated earlier and explained further below, an energy upgrade investment will not be effective when applied in a building of questionable structural integrity.

3 A brief overview of seismic and energy retrofitting solutions

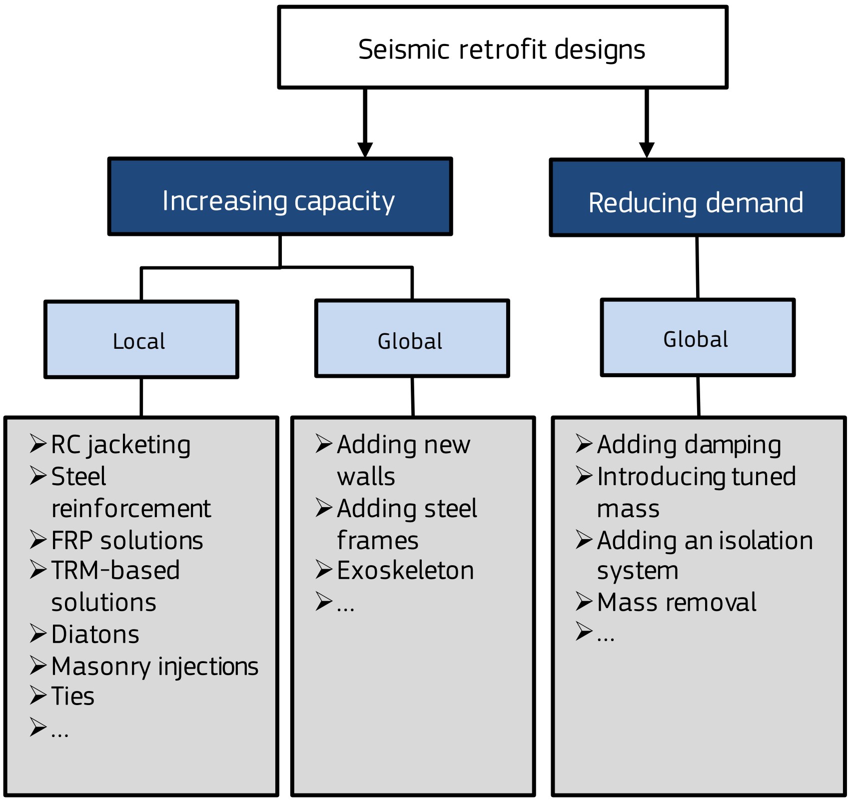
As highlighted in the previous section, the existing building stock of EU countries has several deficiencies in terms of their level of seismic design and energy efficiency. In this Section, current solutions for seismic and energy retrofitting are briefly described separately to provide a context and background to the technologies for combined retrofitting presented in Section 4.

3.1 Current seismic retrofitting interventions

To be effective, a seismic retrofit measure should accomplish one of the two main objectives: to reduce seismic demand or to increase capacity. In addition, seismic retrofit strategies can be classified into **global interventions**, if they modify the global behaviour of the structure, or **local interventions** if they enhance the performance of the weakest existing elements. Some of the choices that may be adopted for strengthening existing buildings against seismic action can be conceptually, and schematically (see **Figure 5**), subdivided into these main categories:

- Increasing capacity by intervening on existing elements. The damage and collapse modes can be modified by **locally** increasing the strength of the elements, to increase the capacity and eliminate possible brittle failures, or by increasing the deformation capacity of the elements, in particular the deformation capacity of the critical sections of beams and columns.
- Increasing capacity with insertion of additional elements. The systems are conceived to increase strength and stiffness and eventually to regularize the torsional response of the building and may lead to a **global** change in the behaviour of the building. This intervention is generally based on steel-braced frames or concrete walls that can be inserted in the interior or, better, outside the building.
- Reduction of demand. A **global** intervention to achieve a reduced seismic demand, either by introducing seismic isolation systems or adding damping or tuned masses to reduce the displacement demand.

Figure 5. Seismic retrofitting strategies.



To assess the effectiveness of an intervention, three main properties have to be examined: strength, stiffness and ductility. The effect of different retrofit measures on the behaviour of RC buildings is summarised in **Table**

1. Local measures mainly affect the mechanical properties of individual members and are preferred when the structure at hand has more or less adequate force resistance, but not enough ductility. On the other hand, global measures also bring about a significant increase in the force resistance of a structure and are more economical to use in cases where the existing resistance is too low.

Table 1. Effect of local and global retrofit measures on building properties.

	Technique	Strength	Stiffness	Ductility	Irregularity	Force demand	Deformation demand
Local measures	RC/mortar jacketing	+	+	+		-	+
	Steel jacketing	+		+			
	FRP/TRM jacketing	+		+			
	Hybrid jackets	+		+			
Global measures	Bracing systems	+	+		+	-	+
	Shear walls	+	+		+	-	+
	Infills	+	+		+	-	+
	Mass reduction				+	+	-
	Seismic isolation		-		+	+	+
	Energy dissipation systems		+/-				+

Source : based on Gkournelos et al., 2021.

In the following sub-sections, local and global measures for seismic strengthening are briefly introduced. A detailed description of seismic retrofitting solutions is however not within the scope of this report and the reader is hence referred to recent state-of-the-art reviews on this topic (da Porto et al., 2018; Gkournelos et al., 2021; Triantafillou et al., 2021).

3.1.1 Local measures

Depending on the building type, different local retrofitting techniques can be applied. These can make use of conventional materials like steel and concrete, or more modern fibre-based composites.

In **RC structures**, the most usual form of localized strengthening is by jacketing individual columns, beams and beam-column joints. Jacketing techniques are mainly used to increase the axial capacity, shear strength and ductility of such elements. Conventional jackets made of concrete and reinforcing steel or structural steel elements were the first to be examined by researchers and applied by engineers (e.g.: Abdullah and Takiguchi, 2003; Varum, 2003). Moving to recent years, fibre composites started being used more widely due to their better mechanical properties and durability. Fibre-reinforced polymer (FRP) sheets or laminates attached to RC elements using epoxy resins can lead to a substantial increase in their bearing capacity (e.g.: Antonopoulos and Triantafillou, 2002; Akguzel and Pampanin, 2012; Pohoryles et al., 2018; Pohoryles et al., 2019; Pohoryles et al., 2021). More recently, textile reinforced mortars (TRMs) have started being examined as an alternative to their FRP counterparts, as they are more economical, easier to apply and more resistant to high temperatures and fire (e.g.: Raoof and Bournas, 2017b; Cerniauskas et al., 2020).

Similar techniques can be applied to **masonry structures** to upgrade the behaviour of individual wall elements. For example, repair works can be carried out by grout and epoxy injection inside cracks for low load requirements (e.g.: Manzouri et al., 1996). Alternatively, steel reinforcement in the form of rebars can be used either externally (in the form of conventional reinforced plastering), or internally along grooves, that way significantly improving the element's in- and out-of-plane response (e.g.: Baloević et al., 2016). Post-tensioning solutions may also be applied in such scenarios, greatly enhancing the overall behaviour of existing members, however, their implementation is generally more difficult (e.g.: Turer et al., 2007). Fibre-based solutions with FRPs or TRMs are also possible, with the latter being more effective due to their ease of application and better compatibility with the masonry substrate (Kouris and Triantafillou, 2018).

3.1.2 Global measures

Instead of trying to upgrade the behaviour of each structural member, it can be more effective to opt for a global retrofitting measure, especially when dealing with a structure of low initial lateral stiffness and resistance. Global measures are generally more versatile, in the sense that they can be applicable with minor changes for different cases of structure types. They can aim to either (1) improve the structure's characteristics (capacity, ductility, integrity etc.) or (2) reduce the effects of the external loads.

3.1.2.1 Structure improvement

A major capacity increase for an existing structure can be achieved through the addition of new load resisting, wall-like elements at selected places. A typical example is the construction of new RC walls or the infilling of a selected frame with RC; rocking walls may also be used instead of conventional ones, in which case damage and strength degradation are minimised (e.g.: Wada et al., 2009; Görgülü et al., 2012; Benavent-Climent et al, 2018). Alternatively, steel braces can be attached to selected frames using various configurations; concentric, eccentric, buckling-restrained brace (BRB), metal shear panels or even post-tensioned cables (e.g.: Ghobarah and Elfath, 2001; Özel and Güneyisi, 2011; Almeida et al., 2017). Last but not least, masonry infills can also be employed to increase the lateral resistance of selected frames. Especially when strengthened with FRPs (e.g.: Erol and Karadogan, 2016) or TRM (e.g.: Koutas et al., 2015; da Porto et al., 2015; Koutas and Bournas, 2019; Pohoryles and Bournas, 2020a; Pohoryles and Bournas, 2020b), they can provide a reliable resisting mechanism, able to dissipate significant lateral forces.

For **masonry** buildings, one of the major weaknesses usually encountered is the lack of structural integrity. This may result in the partial collapse of parts of such buildings, because of their inadequate connection to the neighbouring elements. The improvement of their integrity is the most effective way to achieve a reliable response of masonry buildings, as in such structures, a box-type behaviour is generally preferred (Tomazevic, 1999). This can be achieved by constructing, for example, confining RC elements, or columns at wall intersections and intermediate spots, connected by a ring-beam, that ties the structure together at the floor levels (e.g.: Borri et al., 2009). An alternative way to ensure a uniform distribution of loads is through the creation of reliable and stiff floor diaphragms, through which the lateral forces are distributed to the resisting elements. The stiffening of horizontal diaphragms can be achieved through various ways, including the addition of wood planks (e.g.: Modena et al., 2004) or timber panels (e.g.: Branco et al., 2015) on existing timber floors, the use of diagonal bracing with steel or FRP strips (e.g.: Gattesco and Macorini, 2014), as well as metallic ties (da Porto et al., 2018). Finally, the complete replacement with stiffer RC slabs is also possible, although it may add significant weight to the structure. In any case, the connection between the diaphragm and the supporting masonry walls is of utmost importance and extra care should be taken, otherwise, the transfer of loads will not be possible. For even greater effectiveness, this method may also be used along with the previous ones. In general, besides specific interventions for the roof elements (e.g., the repair of wooden trusses, or the local strengthening of RC beams, etc.), the interventions described for the seismic improvement of floors can be also applied to the roof pitches.

3.1.2.2 Load reduction

For seismic strengthening applications, increasing a building's capacity might not always be the most effective retrofitting scheme. As the previously mentioned techniques significantly increase the lateral stiffness, they also lead to the attraction of higher seismic forces. When combined with soft soil beneath the foundation of the structure at hand, these forces can lead to the activation of a global overturning mechanism. Furthermore, when floor accelerations need to be limited, capacity increasing techniques are not effective at all. Finally, the intervention on an existing building might prohibited for either cultural or operational reasons. In all these cases, an alternative route needs to be followed.

A possible way to tackle the above-mentioned problems is through base isolation. The basic idea is to decouple the superstructure from the underlying foundation soil to minimize the vibrations that a building will perceive during a strong ground motion (e.g.: Natale et al., 2021). This is achieved using isolator systems (elastomeric bearings, lead-rubber bearings, friction-pendulum bearings etc.), which significantly increase the structure's natural period, leading to lower spectral accelerations, and in turn lower base shear demands. At the same time though, the spectral displacements are also increased, which is why in many cases these systems are coupled with damping devices

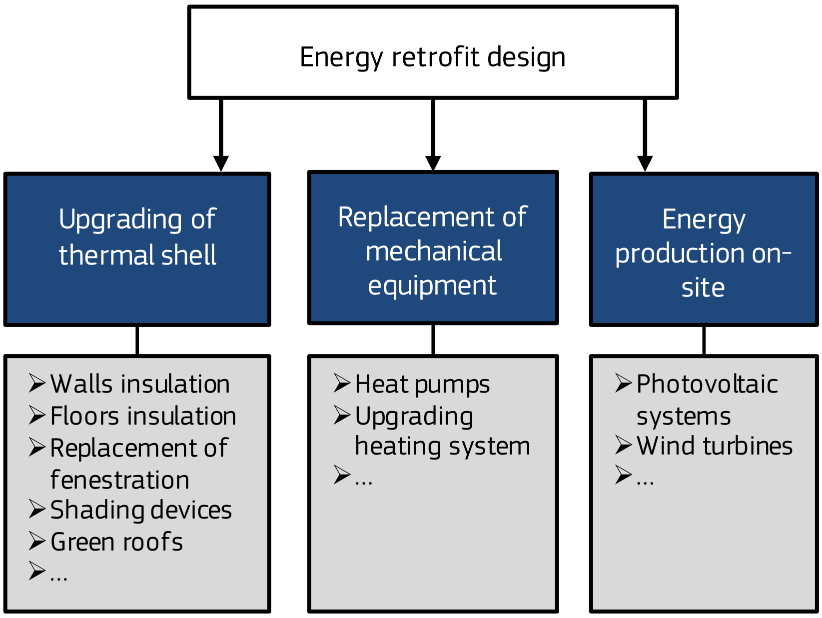
Dampers can be used alone or combined with base isolators. In any case, their objective is to act as regions of excessive energy dissipation, so that the structural elements remain practically elastic and undamaged. There are various types and designs of seismic dampers, such as viscoelastic, friction, viscous fluid, and tuned mass dampers (e.g.: Lee and Kim, 2017; Nakai et al., 2019; Oinam and Sahoo, 2019); all of these systems act passively when loaded. Apart from those, there are also active or semi-active systems (e.g.: Pohoryles and Duffour, 2015; Priya and Gopalakrishnan, 2019) that make use of real-time sensors and signal processing controllers, but their application is limited.

3.2 Energy upgrading of buildings

In general, there are three main solutions (see **Figure 6**) for tackling the poor energy efficiency of existing buildings and enhance their energy performance:

- **Upgrading of the thermal shell**. In older buildings, it is common to have walls with poor thermal behaviour. To minimise thermal losses and hence building energy demands, an upgrading of the thermal shell is often necessary. Typically, this is achieved by attaching thermally insulating materials to the external wall surfaces together with a protecting finishing layer. Additionally, old fenestration systems also typically requires upgrading, namely their replacement with highly efficient windows and doors.
- **Replacement of the mechanical equipment.** A second way to enhance the energy performance of existing buildings is by replacing the old and inefficient mechanical equipment. Nowadays, highly efficient heat pumps combined with ventilating equipment can satisfy current energy needs at low consumption, thus reducing the building energy demand.
- **Energy production on-site** through Renewable Energy Source (RES) systems. A third solution, which is often combined with the others, allows to reduce the energy purchase and to save money. In general, renewable energy sources help reducing air pollution and cutting CO_2 emissions, however, RES systems do not improve the energy efficiency of the building itself.

Figure 6. Energy retrofitting strategies.



3.2.1 Retrofitting with thermal insulation

The outer shell of a structure is comprised of vertical (walls, doors, and windows) and horizontal surfaces (roofs, foundations/slabs on ground) through which heat can travel. Therefore, the greater the thermal resistance of these surfaces, the easier and more economical it will be to maintain the inner temperature within comfortable limits. The external envelope plays a fundamental role in the thermal behaviour of a building, since it is a border between the internal and the external environment, influencing the thermal comfort of the inhabitants and the energy loss during the operating phase (Jelle, 2011).

3.2.1.1 Thermal insulation materials

The occurrence of thermal losses through opaque walls represents a large amount of the whole energy loss from a building (Asdrubali et al., 2013), so the use of adequately insulated walls has become essential. The thermally insulating material is the layer that mainly contributes to the thermal behaviour of the opaque walls. These thermally insulating materials must guarantee an acceptable performance throughout the whole life cycle of the building, but the thermal performance is not the only parameter that should be addressed when selecting an insulator. Indeed, the choice of these materials in the building sector is starting to be inspired by a holistic approach, which considers also non-thermal features such as sound insulation, fire resistance, water-vapour permeability and impact on the environment and human health (Jelle, 2011).

Typical thermal retrofits nowadays use mineral wool or polystyrene products as insulation material, which have λ-values around 35 mW/(mK) (Schiavoni et al., 2016). Detailed reviews of thermal insulation materials can be found in the literature (e.g.: Aditya et al., 2017; Jelle, 2011; Papadopoulos, 2005; Schiavoni et al., 2016). A summary of materials based on these reviews is offered below and where typical thermal conductivity values (λ-values) are given in **Table 2**.

- Traditional materials like mineral wools include glass wool (e.g., glass fibre) or rock wool (made from melted basalt, diabase or dolerite), normally produced as mats and boards. Typical λ-values can be between 30 and 40 mW/(mK). Another material is expanded polystyrene (EPS), which consists of small spheres of polystyrene containing an expansion agent, hence creating a porous material usually cast as boards. Using instead melted polystyrene and adding an expansion gas, extruded polystyrene (XPS) can be produced. Continuous lengths of XPS can be obtained by extrusion with pressure through a nozzle. For both these materials, typical λ-values also vary between 30 and 40 mW/(mK). Polyurethane (PUR) is another closed porous material obtained from an expansion process using an expansion gas. Boards of PUR are available, and in addition the material can also be used as an expanding foam, achieving very good thermal performance with λ-values typically between 20 and 30 mW/(mK). An issue with PUR is however the release of toxic gases in case of a fire. Natural materials, such as cellulose obtained from recycled paper or wood fibre mass can also be used as insulation material. It has a similar consistency to wool and can be found as filler material or as insulation boards and mats with thermal conductivity values around 40 mW/(mK). Slightly higher values up to 50 mW/(mK) are typically obtained for insulation boards made from cork.
- More advanced materials for thermal insulation include vacuum insulation panels (VIP), which consist of a core of porous material of low thermal conductivity (e.g. fumed silica) protected by an envelope of good mechanical strength and very low gas (air and vapour) diffusion properties. This includes metal foils, metallized films and polymer films. Very low thermal conductivity values of 3.5 to 8 mW/(mK) can be obtained for VIPs. Another type of advanced panels are gas-filled panels (GFP), which instead contain a low-conducting gas (such as argon or krypton) protected from the external environment. Low theoretical thermal conductivity values have been reported for GFPs, however, product values are considerably higher, e.g. around 40 mW/(mK). Finally, aerogels are a class of material gaining increasing attention in the last years. The material is characterised by a very high porosity produced by drying a silica foam, leading to porosities up to 99.8 vol% and hence very low densities and thermal conductivities. The material can be used as granular aerogel within window cavities, as full panels or as an additive to stone wool. While the thermal conductivities of aerogels can be extremely low, materials available for construction have typically higher λ-values between 12 and 20 mW/(mK). Aerogels have also been used as additives to finishing plasters in lower volume percentages (ca. 2%) achieving improved thermal performance compared to normal plasters (Berardi, 2017; Kim et al., 2013).

Thermal insulation material can take various shapes and forms, including (1) the typical rolls of soft blanket insulation, (2) more rigid foam or fibre boards, e.g., made from mineral (glass or rock) wool, (3) liquid foam insulation materials, that can be poured, injected, or sprayed, (4) insulation panels, such as vacuum insulation panels, or (5) active systems, such as capillary tubes, that actively heat the walls.

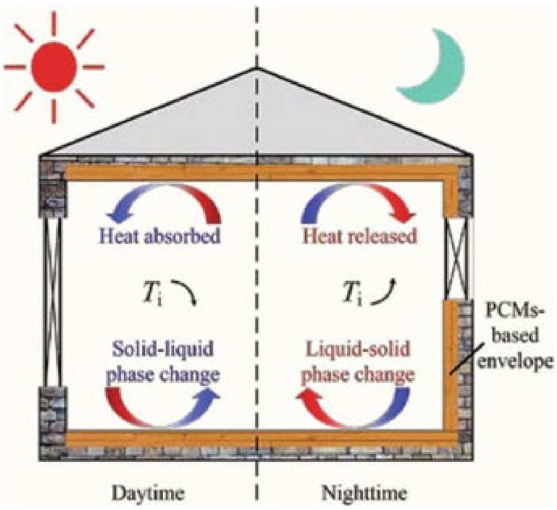
Table 2. Thermal insulation performance of different thermal insulation products.

	Thermal conductivity λ (mW/(mK))	Density ρ (kg/m^3)	Fire class	Form
Traditional materials				
Stone wool	33-44	40–200	A1–A2–Ba	rolls, boards
Glass wool	31-37	15–75	A1–A2	rolls, boards
Expanded polystyrene (EPS)	31-38	15–35	E	boards
Extruded polystyrene (XPS)	32-37	32–40	E	boards
Polyurethane (PUR)	22-30	15–45	E	boards, foams
Cellulose	37-42	30–80	B–C–E	rolls, boards, loose
Cork	37-50	110–170	E	boards, loose, additive
Advanced material systems				
Vacuum insulation panels (VIP)	3.5-8	160–230	A1c	boards
Gas-filled panels (GFP)	10-40	N.A.	N.A.	boards
Aerogel	13-20	70–150	C	rolls, boards, additive

Sources: Aditya et al., 2017; Jelle, 2011; Papadopoulos, 2005; Schiavoni et al., 2016

Although not thermal insulation materials by themselves, phase change materials (PCM) still represent a possible part of the thermal building envelope, and which may be used for thermal building retrofitting applications. PCMs can store and release heat as latent heat changing phase during daytime and night-time as shown in **Figure 7** (Yang et al., 2019). PCMs change the phase from solid state to liquid state when heated, thus absorbing energy in the endothermic process. When the ambient temperature drops again, the liquid PCMs will turn into solid state materials, while giving off the earlier absorbed heat (Jelle, 2011). A review of main PCM materials and their applications was recently presented by Duraković (2020).

Figure 7. Principle of PCM-based envelope.



Source: Yang et al., 2019 (CC BY 3.0)

3.2.1.2 Additional considerations

When considering improving the energy efficiency of existing buildings through thermal insulation, next to the aspect of available retrofit materials, it is important to consider that an existing building already has its foundation, walls and roof. Thereby any retrofitting measures should be suitable with and conform to the existing building envelope. Challenges and restrictions might arise concerning material types to be used, thickness restrictions of the thermal insulation for both interior and exterior retrofitting, various wall protrusions and decorations, windows, roof protrusions and heat bridges among others.

Exterior thermal insulation retrofitting is usually regarded as superior to interior retrofitting when only focusing on the thermal improvement, i.e. increasing the thermal resistance and hence reducing the U-value (thermal transmittance) of the building envelope. Thus, if possible, one would often attempt to retrofit the exterior walls, whereas the roof and especially the floor towards the ground may be rather difficult to cost-effectively retrofit from the exterior. Nevertheless, there are also some advantages with interior retrofitting, e.g. an interior retrofitting does not change the exterior appearance of a building and that none of the possible restrictions for changing or modifying an exterior facade or roof (e.g. antiquarian and heritage restrictions, architectural restrictions, decorations and ornamentations, various protrusions, windows, roof protruding) will apply to the interior. A summary of the advantages and disadvantages of interior and exterior thermal insulation retrofitting of a building is given in **Table 3**.

Table 3. Advantages and disadvantages for interior and exterior thermal insulation retrofitting of a building.

Location	Advantages	Disadvantages
Interior	➢ Does not change the exterior appearance. ➢ No considerations to possible restrictions for changing or modifying an exterior facade or roof will apply ➢ No time or costs for the erection of exterior scaffolding and similar. ➢ Independent of outdoor conditions like e.g. weather, season and various climate exposures.	➢ Far more inconvenient and cumbersome for the occupants during the insulation retrofitting. ➢ Worse thermally with respect to heat bridges, which lead to lower thermal comfort as the floor close to exterior walls may feel too cold. ➢ Reduction in the indoor living area. ➢ Leads to a colder facade surface which may increase the risk for frost shattering during freeze-thaw cycles. ➢ Only small heat storage possible from the warmer inside of the building. ➢ Issue of interstitial condensation, if retrofit is not adequately designed, leading to potential moisture issues or mould growth.
Exterior	➢ Far less inconvenient and cumbersome for the occupants during retrofitting. ➢ Better with respect to heat bridges leading to improved thermal comfort. ➢ No reduction in the indoor living area. ➢ The original facade is protected from climate exposure (e.g. solar radiation, wind, snow, ice, moisture and temperature movements). ➢ Warmer facade and roof surface decrease the risk for frost shattering during freeze-thaw cycles. ➢ Rehabilitation of the exterior facade and roof surface (when exterior rehabilitation is either required or desired). ➢ Heat storage possible from the warmer inside of the building. ➢ Possible reduced corrosion of reinforcement steel in concrete due to reduced moisture level in the concrete.	➢ Possible restrictions for changing or modifying an exterior facade or roof. ➢ Can be difficult to recreate approximately an identical facade as the original one, especially with decorations, ornamentations and similar. ➢ The implementation may be dependent upon outdoor conditions (e.g. weather, season and various climate exposures). ➢ Costs related to the erection of exterior scaffolding and similar. ➢ Noise from the retrofitting activities to the outdoor surroundings. ➢ Difficult to retrofit the floor towards the ground from the exterior, and often also the roof.

3.2.1.3 Upgrading fenestration and reducing solar heat gains

For glazed surfaces, like doors and windows, normally the only way of energy upgrading is their replacement. Nowadays, many options of multi-pane windows and highly efficient fenestration surfaces exist in the market, which can have up to six times higher thermal resistance compared to older ones, hence significantly reducing the energy need for heating and cooling. This is particularly important in older buildings, in which single glazed fenestration without an insulating frame, with U-values as high as 4.5 W/(m^{2}K) - 5.6 W/(m^{2}K), are commonplace (OECD/IEA, 2013). Up to 60% of a building's energy losses can be associated with windows (Jelle et al., 2012). This is not only due to the low thermal resistance of older windows, but also due to significant losses through air penetration if windows do not seal completely when closed. The effect of substituting windows with new ones is not only in the improved thermal resistance, but it can additionally improve the airtightness of a building and provide an improvement of thermal and acoustic comfort.

For the residential sector in the EU, modern, highly insulated windows (e.g. double-glazed windows with low-emissivity coatings, low-conductive frames, and inert gas) have much lower U-values of ca. 1.1 W/(m^{2}K) (OECD/IEA, 2013). New developments in the sector, including triple-glazing (e.g. Juras, 2018), vacuum glazing (e.g.: Memon and Eames, 2017; Qiu et al, 2019) or the use of aerogels (e.g. Buratti et al., 2017) can reduce the U-value of window glazing to values between 0.25 and 0.5 W/(m^{2}K) (Jelle et al., 2012). New technologies such as smart adaptive windows can reduce solar heat gains through the use of thermochromic, photochromic or electrochromic glazing (Tällberg et al., 2019), while photovoltaic glazing (e.g.: Radwan et al., 2020; Ghosh et al, 2018) can be used to complement the energy needs.

Windows with a reduced solar heat gain factor represent one option to reduce the heating effect of solar radiation, potentially leading to high reductions in total energy use (Ahn et al., 2016). Additionally, solar heat gains can be reduced through the implementation of different shading devices. These may be passive louver systems or active ones (e.g.: Barozzi et al., 2016; Hosseini et al., 2019). The effect of improved shading is a reduced energy use for cooling and an improvement in thermal and visual comfort.

Finally, the use of green facades, i.e. completely or partially covering roofs with greenery, can also be used to achieve an improvement in energy use for heating and cooling, through improved thermal insulation (e.g.: Hunter et al., 2014), while also providing an architectural renovation with aesthetic and physiological benefits to the urban environment (e.g.: Smardon, 1988; Sheweka and Mohamed, 2012). Green façade elements are increasingly used as a design feature to reduce building energy consumption, but can also have broader effects for the urban adaptation to a warming climate (Sheweka and Mohamed, 2012).

3.2.1.4 Floors and roofs

Several strategies may be employed to improve the energy efficiency of floors and roofs. These strategies can be applied separately, or combined, depending on the required level of energy improvement.

- **Floor or roof insulation**: very often basements (as well as attics) are not air-conditioned. In these cases, the heat loss through the floor and the roof can represent a deficiency in the energy behaviour of the building. It is possible to prevent this effect by including thermal insulation (eg. using the materials presented in 3.2.1.1in the floor or roof configuration. This intervention can be applied to every type of horizontal diaphragm (wooden, RC, steel).
- **Reducing heated/cooled volume**: the intervention involves the insertion of an insulating false ceiling (e.g.: AbdelRazek et al., 2015), which allows to reduce the heated/cooled volume, thus decreasing the energy demand. This intervention can be applied on every type of diaphragm (wooden, RC, steel), although in some cases, the intrados appearance of some historic types of floors (particularly in the case of wooden floors or steel floors with vaulted clay tiles, etc) needs to be preserved.
- **Ventilated roof systems**: A ventilated roof presents an air cavity between the structural layer and the finishing layers (e.g.: Kain et al., 2020). This cavity permits to let out steam from indoors during the winter months and reduces stagnation of heat during the summer months, hence significantly reducing the energy need of the building (Dimoudi et al., 2006).
- **Green roofs:** The use of vegetation planted on the roofs of existing buildings can serve multiple purposes, with benefits for the individual building, such as cooling (Del Barrio, 1998), aesthetic and psychological improvements for inhabitants (Smardon, 1988) or absorption/buffering of rainwater, but additionally also having a positive effect on the urban environment, through

pollution abatement (e.g.: Rowe, 2011; Berardi et al., 2014) or by lowering urban air temperatures and reducing the heat island effect (e.g.: Oberndorfer et al., 2007; Vandermeulen et al., 2011).

- **Upgrading energy systems through radiant floors**: the most common heating system in existing buildings is through radiators. Intervening on the floor creates the opportunity to upgrade the heating systems, by replacing the radiators with *radiant floors* (e.g.: Ahn, 2011). In radiant floors, the heat is distributed more evenly, furthermore also increasing the thermal comfort, hence ensuring a decrease in the energy required for heating. In addition, if combined with a heat pump, radiant floors can be used in winter as well as during summer months as an air-cooling system. This intervention can be applied to every type of diaphragm (wooden, RC, steel).

3.2.2 Upgrading of mechanical equipment and energy production

While upgrading the building envelope through thermal insulation and fenestration replacement represent very effective means to reduce a building's energy consumption, this is typically not sufficient to achieve improvements to the level of NZEB (near-zero energy buildings). The possibility for reducing energy losses associated with older, inefficient HVAC systems, as well the generation of additional energy, e.g. through photovoltaic (PV) panels are possible supplementary interventions in energy refurbishments of buildings that can contribute to this goal.

Interventions on the HVAC system include the installation of thermostatic valves, replacement of boilers with more efficient ones, and installation of heat pumps or the installation of local or central heat recovery ventilation systems (Clark, 1997). HVAC retrofitting or replacements not only reduce the energy use of a building but can also increase indoor thermal comfort, reduce the possibility of mould formation and reduce the concentration of hazardous substances in the air (Žegarac Leskovar and Premrov, 2019).

The installation of building-integrated photovoltaics (BIPV) is the most typical application of on-site energy generation found in buildings (Evola and Margani, 2016). BIPV systems generate renewable electricity by converting energy from solar radiation. Photovoltaics can be integrated into the roofs, facades, but also windows and shading elements of a building (Jelle, 2016; Tällberg et al., 2019). As such, they can serve at the same time as energy harvesting elements, climate screen, as well as architectural elements. Various forms of BIPV products exist, including foils, (roof) tiles, modules and solar glazing (Jelle and Breivik, 2012). In combination with other energy efficiency interventions, as discussed in the previous sub-sections, BIPV systems may be an integral part of energy retrofitting, with the potential of creating sufficient electrical energy to support the systems of a building, leading to zero energy or even positive energy buildings (e.g.: Dobrzycki et al., 2020; Gholami et al., 2021).

Incorporating the energy source within the building, i.e. close to the electrical demand, reduces the need for expanding high voltage electricity networks within urban environments, eliminates losses along such networks and can be instrumental in creating a more flexible, reliable and smarter urban electricity grid (Batista et al, 2013). Other energy-generating technologies, such as small building-mounted or building-integrated wind turbines also exist but are less commonly found. In particular, vertical axis wind turbines (VAWTs) have the potential for small scale power production in urban environments. Their design is adapted to small installation spaces and can reduce vibrations and hence unwanted noise pollution. Additionally, they may be designed to take advantage of the urban low and turbulent wind speed characteristics (Ishugah et al., 2014).

4 Integrated seismic and energy retrofitting technologies and concepts

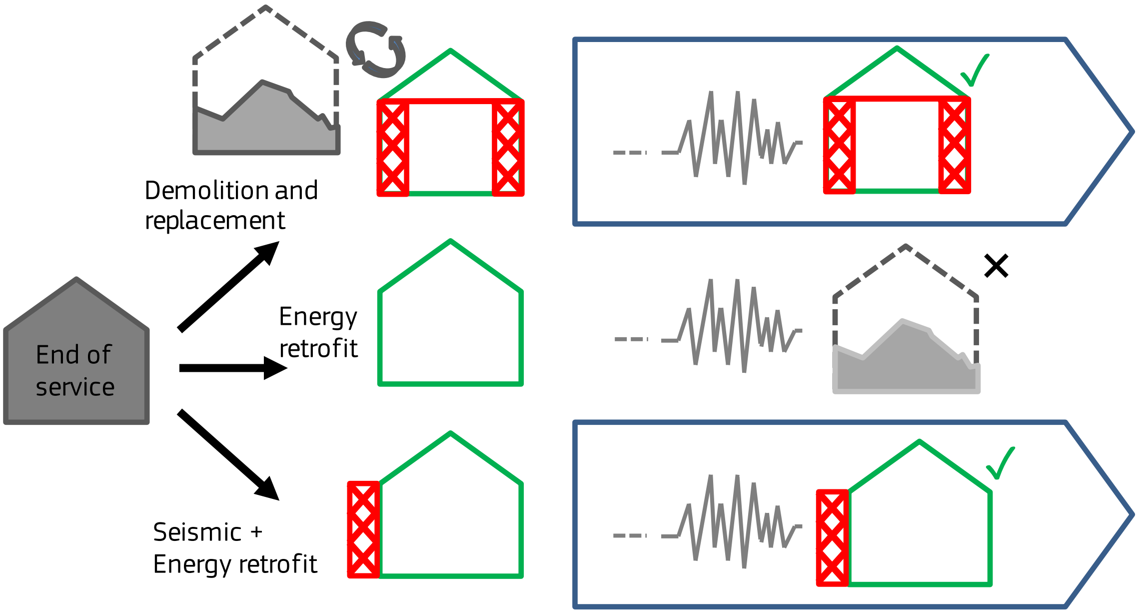
Up until very recently, structural and energy retrofitting have been thought of as two independent schemes that could be applied to an existing building. This way of thinking started changing when the first failures of energy-upgraded structures started taking place (see **Figure 8**). Such failures and collapses of retrofitted buildings made clear that no investment is safe unless the building itself is safe and that the two modes of retrofitting (structural and energy) are not independent, but rather highly dependent on each other.

Figure 8. Collapse of an RC building, which received only energy retrofitting after the 2012 Emilia-Romagna earthquake.

Source: Marini et al. 2016 © European Union.

Figure 9 compares two cases of retrofitting applied to an existing building. In the first one, a sole energy retrofit is selected, which leaves it vulnerable to a potential high-intensity seismic event. If such an event does occur within the structure's lifespan, it is most likely that damage will be caused. Depending on the event's intensity, that could mean anything from the need for minor repair works to the need for a total replacement of the building. Obviously, in such a case, along with the building itself, the energy retrofit is affected and might be destroyed as well.

Figure 9. End of service life of buildings: The effect of (1) Demolition and rebuilding; (2) Energy upgrading and (3) integrated energy and seismic upgrading in zones of seismic hazard.



Based on: Belleri and Marini, 2016.

On the other hand, if an integrated structural and energy upgrading scheme is applied, then the building's structural integrity can be regarded as truly safe. This means that even if a major seismic event takes place, the building will be able to withstand it, without affecting the energy retrofit at all. Practically, in areas of moderate to high seismic risk, it is imperative that any energy retrofit application should only be carried out **after** the building at hand can be regarded as structurally safe, according to modern standards. Otherwise, the risk of losing the energy investment is not justifiable as recent experience has shown.

The need for combined energy and structural retrofitting is nowadays acknowledged and has been reported by a few researchers in the field (Calvi et al. 2016, Belleri and Marini 2016, Marini et al. 2017, Bournas 2018). The application of an integrated retrofitting solution could be as simple as combining two independent techniques of structural and energy upgrading. In this case, the total cost of the intervention would be approximately equal to the sum of the two independent interventions. Undoubtedly, such an approach would demand lots of funds and it might not be possible for states to finance such solutions. That is why techniques that can achieve both goals **at the same time** have a much higher probability of being adopted in real practice since they can be applied at a significantly lower cost.

In the following subsections, a conceptual framework for combining existing seismic and energy retrofitting technologies is briefly introduced first, followed by a detailed state-of-the-art review of all research efforts to date, which explored the integration of seismic and energy retrofitting.

4.1 Conceptual framework for combining seismic and energy retrofitting

When thinking of combining techniques for seismic and energy retrofitting, it is important to consider their compatibility already at the design phase, particularly in terms of: possible spatial overlapping; the scale of application; the level of disruption; and the desired performance level.

Spatial overlapping can hinder the application of either the seismic or the energy technique due to practical constraints they cause each other. The scale of application is related to the number of building components on which the intervention is applied, while the level of disruption is related to the building downtime during which the intervention works must be realised. For instance, if the seismic intervention is needed only on few members of a building, while the energy intervention is foreseen to require works on the entire building, the two interventions may be considered less compatible in terms of scale, but likely also on the level of disruption.

Menna et al. (2021) very recently provided a framework for combining seismic and energy retrofitting interventions to ensure compatibility according to their level of disruption and intrusiveness, performance target and time and cost of the intervention. The proposed framework aims to ensure seismic and energy upgrading interventions can be combined to achieve specific pre-defined seismic and energy performance targets while keeping the level of invasiveness and disruptiveness at the same level. According to Menna et al. (2021), the influence of the seismic strengthening of existing RC buildings can be quantified in terms of the increased safety index $\zeta_E = PGA_C/PGA_D$ at the life safety limit state (LSLS)[1], following the Italian Building code (MIT, 2008), while the energy performance target is expressed in terms of primary energy consumption (PEC) reduction. 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.

As an example, for RC buildings, potential established seismic and energy retrofit techniques can be used in conjunction to achieve improvements in both, the seismic and energy performance. The techniques are categorised by their level of invasiveness according to this framework:

— A **low level of invasiveness** is provided by local interventions devoted to obtaining a limited effect in terms of seismic and energy upgrading being more suitable in areas with moderate seismic hazard and energy demand. Local interventions are intended as those combining interventions for the sole seismic or energy upgrading to obtain both effects. From a seismic point of view, this may consist of a **local intervention** on beam-column joints. This removes potential brittle failure of joints and column ends with an intervention made only from the outside. With this low level of disruption, also energy upgrading should avoid building downtime. Therefore, roof insulation, installation of thermostatic valves and windows replacement is suggested. At this level of intervention, also strengthening of masonry infills against out-of-plane collapse can be made from the outside, without interfering with the building occupancy.

— A **medium level of invasiveness** is related to the combination of previous interventions (both seismic and energy) with the addition of solutions able to postpone also ductile failures of RC members. At this level also column-end confinement (e.g. FRP/TRM/RC jacketing) is proposed to increase ductility and then seismic capacity. This requires some infill demolition, resulting in a more invasive intervention. Consequently, the energy upgrading is complemented, for example, with a layer of insulating material inside the gap of infills.

[1] PGAc is the seismic capacity (in terms of peak ground acceleration), being that causing the achievement of the LSLS and PGAd is the demand PGA (design value) at the building location according to the hazard map.

— Finally, a **high level of invasiveness** is related to **global interventions** like seismic isolation or insertions of dissipative braces, which can strongly modify the seismic behaviour of the building to obtain a significant improvement of seismic performances. Bracing systems have higher invasiveness due to their insertion inside the frames with consequent demolitions. The suggested energy upgrading interventions, in addition to all the previous, are represented by the application of insulation material on the building façade and the replacement of heating/cooling mechanical systems with more efficient ones.

Integrated techniques aim to achieve energy and seismic performance improvement at once, with a single high-engineering system or material. Such a system would guarantee both the required seismic and energy performance levels. While this requires a more in-depth conception and design, integrated systems could reduce downtime and labour costs compared to combinations of separate interventions. Different types of integrated seismic-plus-energy retrofitting solutions are proposed in the scientific literature and can be grouped into:

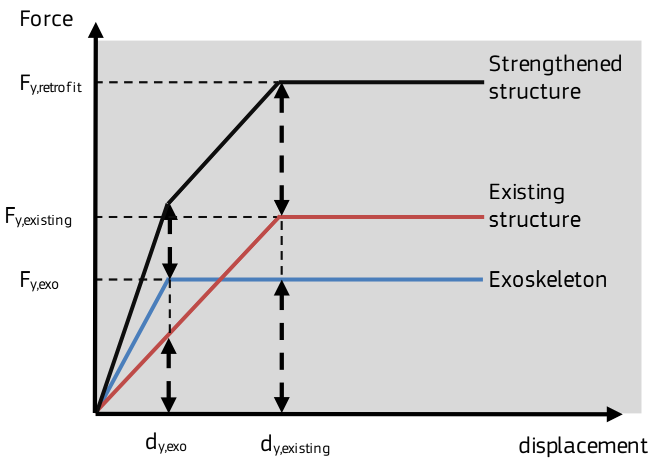
- Exoskeleton interventions (Section 4.2);
- Improvement of envelope elements (Section 4.3);
- Replacement of envelope elements by higher performance elements (Section 4.4);
- Combined Interventions on horizontal elements, i.e. roof and floors (Section 4.5).

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

4.2 Integrated exoskeleton solutions

An exoskeleton is an external self-supporting system (i.e. with its own foundations) rigidly linked to an existing building that is vulnerable to seismic actions (Martelli et al., 2020). Since the 1980s the use of external auxiliary structures is considered one of the possible options for seismic retrofit of existing RC buildings with low dissipative capacity[2]. From a structural point of view, exoskeletons can provide additional strength and stiffness to an existing building as shown in **Figure 10**. It is possible to divide structural exoskeletons into two main categories: (i) wall-like systems (introducing shear walls or braced frames **Figure 11** (a) or (ii) shell-like systems, as in **Figure 11** (b), exploiting a box-structural behaviour (Marini et al., 2017). The two systems are illustrated in **Figure 11**. For a recent state-of-the-art report on the use of structural exoskeletons, the reader is referred to Di Lorenzo et al. (2020).

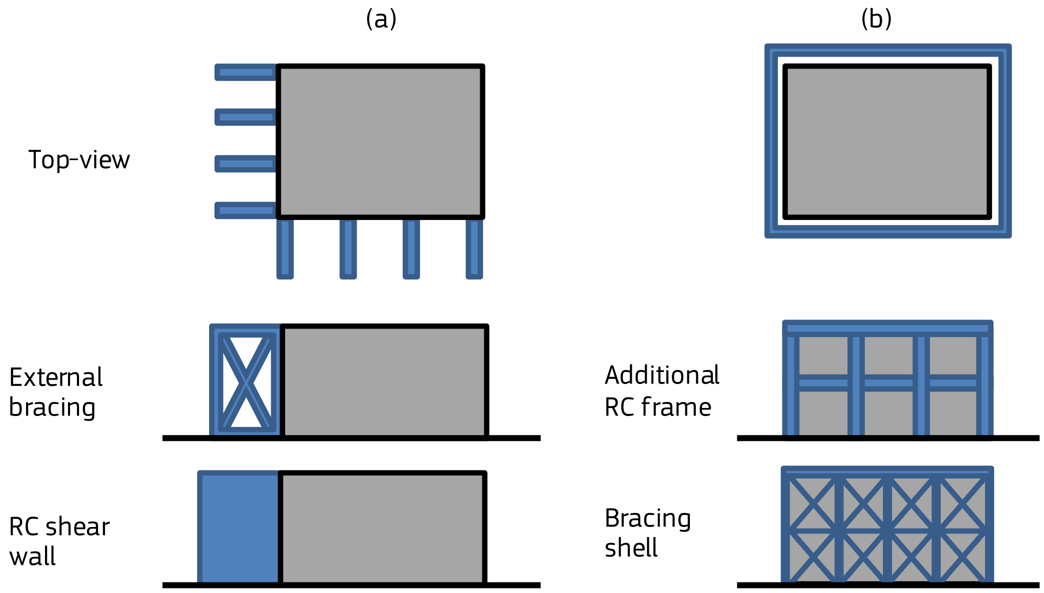
Figure 10. Structural safety's increment provided by an exoskeleton.



Source: elaborated by the authors based on Ferro et al. (2020).

[2] 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 11.(a) Wall and (b) shell layouts for structural exoskeletons.



In wall-like solutions (e.g.: **Figure 11**a), the additional stiffness and resistance are lumped into few elements placed perpendicular to the building façade, namely RC shear walls or steel bracing systems. In the case of very stiff existing structures or highly seismic areas, such a system may not be viable since a significant number of walls may be needed, instead shell or grid-shell solutions may be adopted. As shown in **Figure 11** (b), the façade is wrapped by a whole new external envelope that can increase the seismic resistance of the structure.

Exoskeleton solutions are not always feasible, e.g. in the case of densely built-up areas, which lack space around the structure for the exoskeleton and render excavation works for its additional foundation system difficult (Santarsiero et al., 2021). Furthermore, as the 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, which may render the intervention inapplicable for certain types of 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). Moreover, it gives the possibility for adding new storeys 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.

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). As shown in **Figure 12**, two main ways of integrating structural and energy upgrading within an exoskeleton can be envisaged. In wall systems the energy efficiency upgrade can be achieved by the finishing curtain walls or the envelope attached to the exoskeleton (**Figure 12**a); in this case, the two structural-energetic systems work in parallel. On the other hand, in shell systems, the energy efficiency upgrade and structural safety could be achieved through a dual-use of the same elements (**Figure 12**b).

Figure 12. Structural and energy function in wall systems (a) and shell systems (b).

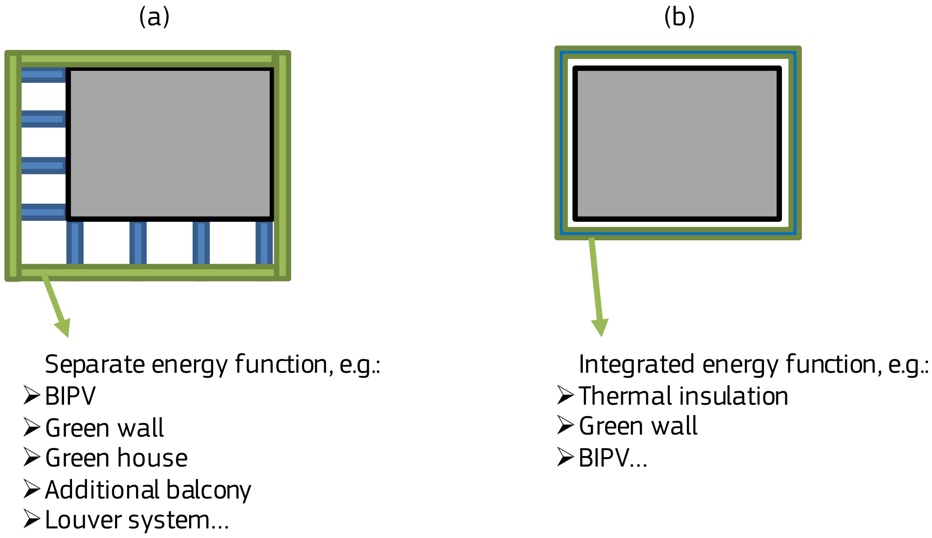
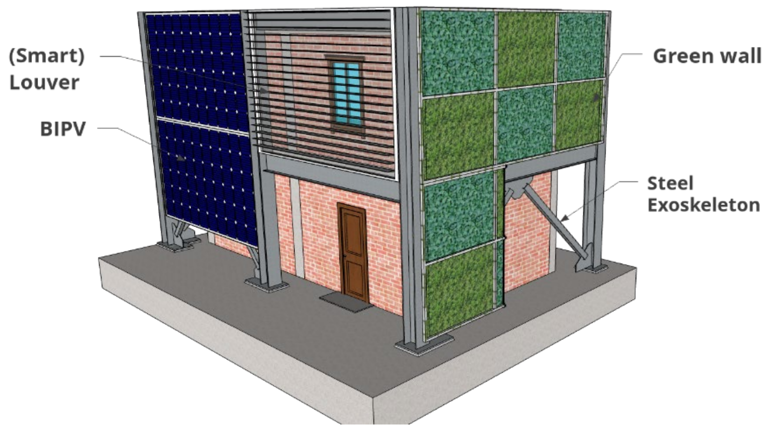


Figure 13 highlights potential energy-efficiency systems that could be integrated within a structural exoskeleton, which would serve as a secondary envelope. For instance, the exoskeleton could also be used to support renewable energy production devices (e.g. BIPVs), or vertical gardens (so-called "green 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 13. Integration of exoskeletons with different energy-efficiency systems.



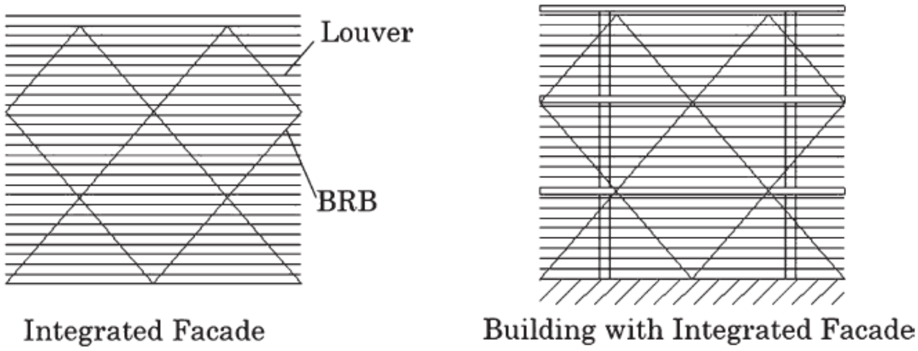
In the following sections, different exoskeleton solutions proposed in the literature for integrated retrofitting are presented. These are split into shell-grid, shell and wall applications, depending on their structural form.

4.2.1 Shell exoskeletons

4.2.1.1 Steel grid exoskeletons

The first combined retrofitting applications appears to be the renovation of the Midorigaoka-1st building of the Tokyo Institute of Technology, completed in 2006. As can be seen, the retrofit also gives the building a modern appearance and integrates an architectural refurbishment of the building. The use of an "integrated façade", consisting of the combined application of a shell exoskeleton, based on Buckling Restrained Braces (BRB) and louvers (as shown in **Figure 14**) was based on the pioneering work by Takeuchi et al. (2005; 2006; 2009). The retrofit application was performed in 9 months without the need for relocation of the tenants (Takeuchi et al, 2009). The BRBs provide the structure with additional seismic energy dissipation capacity, as they are designed to yield under seismic loading and function as hysteretic dampers. An experimental study on RC frames representing those of the Midorigaoka-1st building showed a brittle shear failure of the columns at 0.5% inter-storey drift (ISD), while the BRB-retrofitted frames could sustain 2% ISD without any damage to the frame (Takeuchi et al., 2009).

Figure 14. Integrated façade design with BRB and louvers: concept and scheme.

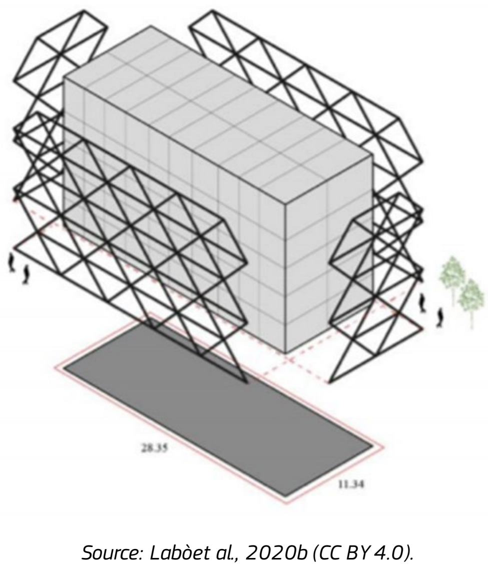


Source: Misawa et al., 2016 (CC BY 4.0).

The same concept was taken further, by using a set of diagonal BRBs, which function at the same time as seismic energy dissipaters and as shading devices for reduced solar gains. This combination was applied for the seismic and energy retrofitting of the administration building of the Tokyo Institute of Technology in 2008. A simulation study on the solar radiation reduction of different BRB/Louver arrangements showed reductions up to 66% for horizontal louvers (as in **Figure 14**) and 55% for diagonal orientations. Through building energy modelling (BEM), it was further demonstrated that due to the reduction in solar heat gains, the energy consumption of a typical Japanese office building could be reduced by 4.7% to 10.7%, depending on its orientation (Misawa et al., 2016).

Labò et al. (2016; 2020a; 2020b) more recently proposed the application of diagonal grids ("diagrids") in the form of a 3D lattice structure as exoskeletons for the sustainable seismic and energy retrofitting of existing RC buildings, as shown in **Figure 15**. The diagrid retrofit can be easily combined with other façade elements, to offer integrated solutions for structural, energy and architectural improvements. From the structural point of view, the diagonal members are designed to intersect at floors of the existing structure, where they are connected to steel horizontal ring beams, which have the double function to stabilize the diagrid exoskeleton and to collect and transfer the seismic forces from the building floor diaphragms to the diagrid and a new foundation system. Concerning their structural response, the members can be designed either as over-resistant or dissipative, depending on the needs of the structure at hand; the former approach is best suited for stiffer buildings, while the latter for more flexible ones. An optimised design approach for the diagrid members, aimed at minimising the impacts and costs of the intervention and throughout the life cycle of the building is presented in (Labò et al., 2020a). Following the principles of Life Cycle Thinking (LCT), the diagrid can be fabricated from recyclable/reusable materials, and repairable, adaptable and fully demountable elements.

Figure 15. Seismic strengthening of RC building with steel diagrids.



Source: Labòet al., 2020b (CC BY 4.0).

Diagrid exoskeletons for holistic architectural, sustainable and seismic retrofitting are also explored by D'Urso and Cicero (2019). Diagrid-type structures are generally more material-efficient than other steel exoskeletons, additionally, a parametric optimisation algorithm was implemented to find the most efficient shape. Different design ideas for integrated retrofitting were then elaborated, as in **Figure 16**, assuming the use of different thermal panels (e.g. solar modules, vegetation, insulation or shading). The additional architectural upgrading is of special interest in the context of the New European Bauhaus, bringing together sustainability and aesthetics.

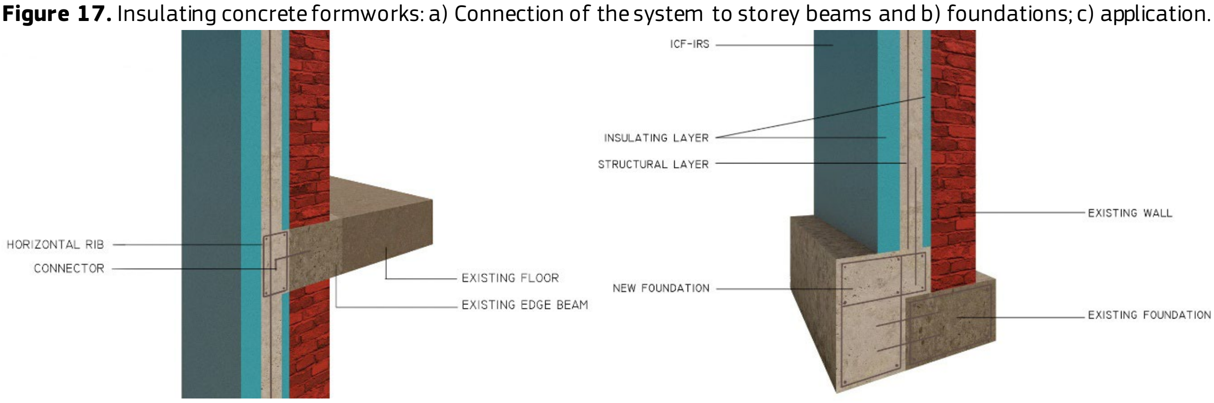
Figure 16. Different design options for a holistic upgrading of RC building with a diagrid exoskeleton.

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

4.2.1.2 Addition of insulated RC walls

Constructing a new structural system with external foundations integrated with a thermal coating has been proposed by Pertile et al. (2018; 2019). The system consists of adding an external shell to the existing building's envelope, which consists of a thin RC wall cast in-situ between pre-assembled layers of insulating material, functioning as permanent formwork (Insulated Concrete Formwork, ICF), as shown in **Figure 17**. 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.

Figure 17. Insulating concrete formworks: a) Connection of the system to storey beams and b) foundations; c) application.



Source: Produced by the authors based on Pertile et al., 2019

The wall's reinforcement is made by a single layer of horizontal and vertical reinforcement that needs to be designed depending on the building's characteristics. In the case of RC buildings, the connection with the existing structure is done through connectors to the beams of the structural frame (**Figure 17**a) and at the foundation level (**Figure 17**b). Regarding the energy efficiency enhancement, the thermal performance of the retrofitted building depends on the type of material used as insulating formwork within the system. For example, the thermal transmittance in the case of using two polystyrene layers with 150 mm total thickness, is equal to U=0.21 W/(m^{2}K), which is under the lower limit foreseen for climate zone F (i.e. the coldest climate in Italy).

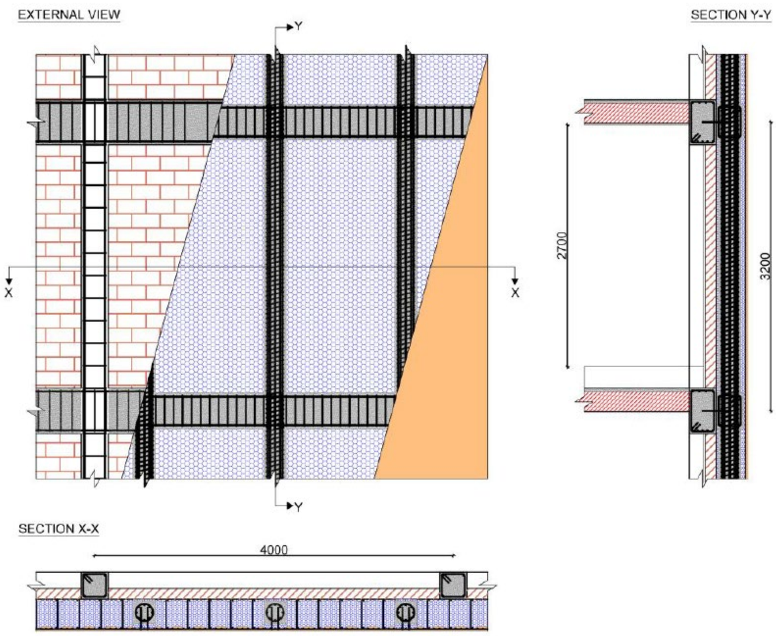
Quasi-static cyclic tests were carried out on two RC frames and two masonry wall specimens upgraded with the proposed system (Pertile et al., 2019). While these tests demonstrate a good connection of the system to the specimens, no quantitative comparisons to non-retrofitted specimens are provided. Moreover, the authors reported the occurrence of a sudden brittle failure and hence suggested the system to be considered as a *non-*

dissipative system in the design calculations for the seismic strengthening. Finally, the use of concrete makes this system not reversible or reusable, and potentially less environmentally friendly.

4.2.1.3 Integrated RC-framed double-skin

Pozza et al. (2021) very recently proposed the concept of an RC-framed double-skin technology for the integrated refurbishment of existing buildings. The shell exoskeleton consists of a tightly spaced, cast-in-place external RC frame system with its own foundation system. The frames are rigidly connected to the existing beams, as shown in **Figure 18**. Prefabricated EPS modules (shown in blue in **Figure 18**) provide the formwork of the RC frame, as well as being the energy retrofitting component. The cross-sections, reinforcement and spacing of the new frame can be adapted to compensate for the lack of seismic capacity of the existing building depending on the specific design target. In an initial FEM evaluation of the retrofit for a single RC frame under pushover loading, the yield force of the strengthened frame doubled, while the displacement capacity increased by around four times. At the same time, the double-skin was shown to improve the U-value of a typical infill wall from 1.86 to 0.15 W/(m^{2}K), as well as showing improvements in sound insulation through acoustic analyses. The presented numerical study is however only a preliminary stage of a more comprehensive research project (TIMESAFE), for which experimental investigations are currently ongoing.

Figure 18. RC-framed double skin solution.



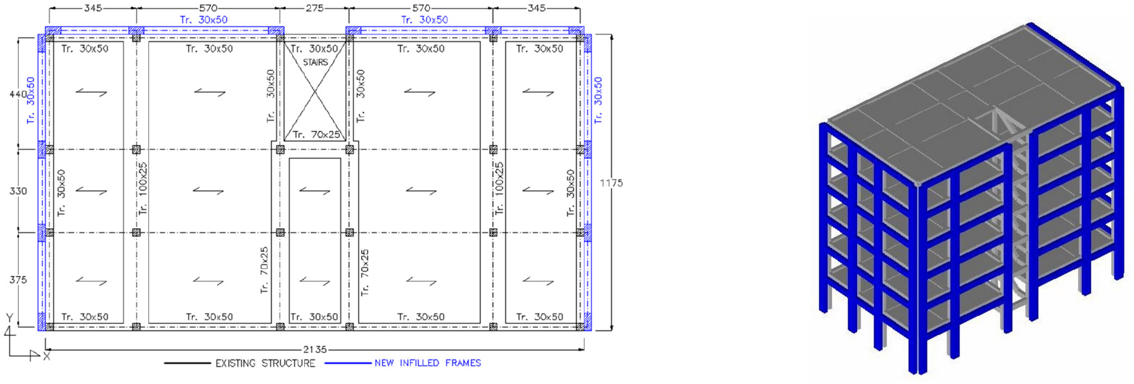
Source: Pozza et al., 2021 (CC BY 4.0).

4.2.1.4 External RC frames with additional infills

Manfredi and Masi (2018) propose a solution for concurrent seismic and energy upgrading employing additional external RC frames, which are connected to the existing building frame to provide additional strength and stiffness. The external RC frame is shown in blue in **Figure 19** for a case-study 6-storey building. Depending on the local seismicity, the external RC members can be purposely designed according to the seismic code of reference. Additional masonry infill walls made from 20 cm thick cored clay bricks ensure improved thermal insulation of the building (U = 0.29 W/(m^{2}K) for the case study building). However, this intervention can be complemented with other energy efficiency solutions which could make it suitable also for more demanding climatic zones.

The case-study building was evaluated numerically for locations in Italy with different seismicity (low, medium, high) in climatic zone E (which corresponds to the largest part of the continental Italian territory). The energy demand was reduced from 74 kWh/year per unit area (energy performance class F), to about 43 kWh/year (class D), while the ratio of seismic capacity to demand could be improved from 0.38 to 1.38 (+263%) for a location of high seismicity. Note that for low and medium seismic hazard locations, only replacing the infill walls without an auxiliary RC frame (see for instance Section 4.4), can be sufficient in terms of seismic capacity, while a similar energy performance can be assumed.

Figure 19. (a) Structural plan of the building and (b) 3D view of the FEM model of the structure with new frames

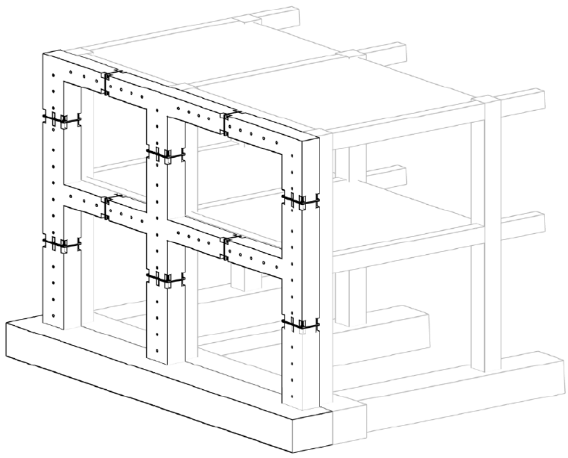


(a) (b)

Source: Manfredi and Masi, 2018 (CC BY 4.0).

Instead of a cast-in-place external RC frame, precast auxiliary RC frames, such as the High-Performance Dissipating Frame system (Manfredi et al., 2021; Manfredi et al., 2018), can also be connected to the existing building frame, as shown in **Figure 20**, and paired with additional infill walls. The RC members of the new frames are precast in the form of beam-column joint sub-assemblies, which are inter-connected through bolted steel plates at column and beam ends. The connection between the new precast members and the existing frame is provided through shear connectors with epoxy resin, designed to resist the shear forces transferred from the existing structure. Additionally, shear damper devices can be employed to provide a higher dissipative capacity.

Figure 20. Precast auxiliary RC frames



Source: Manfredi et al. 2021 (CC BY 4.0)

An example of this is the Santa Maria Bianca hospital of Mirandola (Modena, Italy), which was chosen as a case-study building for the precast auxiliary frame retrofit by Ventura et al. (2019). The structure suffered minor structural damage and severe non-structural damage during the 2012 Emilia earthquakes. The intervention hence considered the presence of the non-structural masonry infills which were previously damaged by the earthquake and caused hospital closure. To avoid damage in case of another strong seismic event, one of the aims of the intervention was the reduction of inter-storey drift values for the design earthquake related to the Damage Limitation limit state. The case study demonstrated the effectiveness of the selected technology in improving the seismic behaviour of the hospital buildings with a consequent reduction of inter-storey drift and a higher seismic capacity also for the Life Safety limit state.

4.2.2 Wall systems

Marini et al. (2017) propose a combined retrofitting system based on a steel-braced shear wall exoskeleton (**Figure 21**a) onto which an energy efficiency system is supported (**Figure 21**b). The latter includes solar greenhouses along the southern façade, as well as thermal insulation (EPS), new windows and shading systems (adjustable louvers) for solar radiation control. The proposed system was evaluated for a case study reference

RC building with masonry infills, built in Brescia, Northern Italy, in 1972. Numerical analyses showed that the proposed system can significantly improve the seismic behaviour of the old, seismically deficient RC building. Through the retrofit, a more uniform distribution of the ISD can be observed. Moreover, the displacement capacity of the retrofitted structure exceeds the displacement demand at the life safety limit state (LSLS) defined according to the Italian Building Code (MIT, 2008). At the same time, the energy performance of the new envelope is also drastically improved, as numerical simulations (stationary thermal analyses) demonstrated reductions of 70% in heating energy consumption.

Figure 21. (a) Shear-wall structure; (b) integrated energy retrofitting supported by the exoskeleton: adjustable louvers, solar greenhouses and filter spaces.

(a) (b)

Source: Bellini et al., (2018) - CC BY 4.0.

The Horizon 2020 funded project *Pro-GET-onE* (Proactive Synergy of inteGrated Efficient Technologies on Buildings' Envelopes) has focused on the use of exoskeletons as a means to achieve structural and energy retrofitting goals (Ferrante et al., 2018) as well as architectural improvements. Different materials were considered for the external structure, including steel and timber frames, as shown in **Figure 22**. In addition to the thermal insulation provided, the external structure also provides energy-efficient buffer zones, helping to reduce solar radiation in summer, providing solar heating in winter, and supporting plug-and-play installations for new HVAC systems. In terms of cost-efficiency, it was estimated that the exoskeleton has a cost 16.5% lower than the combination of typical energy and seismic renovations. This is due to the avoidance of residents' relocation, but also as the real-estate value can be increased significantly, through the increased living space (balconies or extra rooms), enhanced architectural value and user comfort. For a case study in Greece, based on seismic response spectrum analyses, the addition of an exoskeleton with braced steel frames consisting of HEB 240 sections acting as shear walls, can achieve significant reductions in transversal displacement (between 16-26%) at the design earthquake. Additionally, an improvement in energy performance is assumed based on simulations for three case study locations (Greece, Italy and Romania), for which a reduction in energy consumption up to 75% in the winter months and overall reductions of 35% were reported.

Figure 22. Options for exoskeleton retrofit: (a) External steel and aluminium structure; (b) Timber or X-Lam structure.

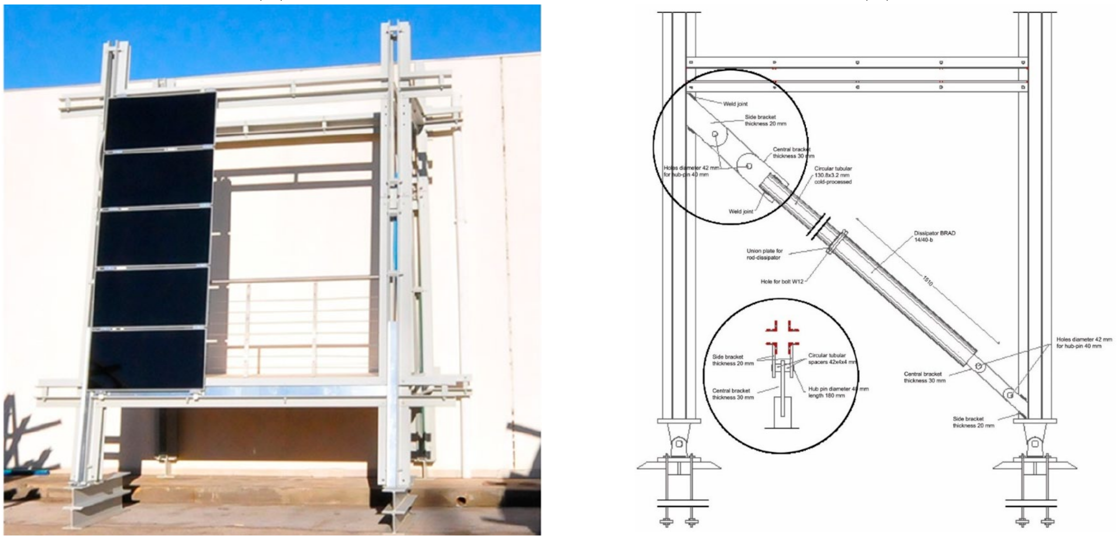
(a) (b)

Source: Ferrante et al., 2018 (CC BY 4.0).

Finally, more recently Foti et al. (2020) built a prototype dissipative frame element, shown in **Figure 23**, to be used as a modular "kit" that allows to seismically retrofit a building, to make it energy self-sufficient and, possibly, also produce positive energy (through photovoltaics). Similarly to the previously described solutions in this section, the elements could also be used to host thermal buffer spaces, shading systems or rainwater collection modules.

Figure 23. (a) Prototype of an element of the dissipative frame exoskeleton with integrated photovoltaics (PV), (b) dissipative BRAD in the perpendicular frames.

(a) (b)



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

Structurally, the beams positioned perpendicularly to the building, provide the connection between the inclined external column and the column in contact with the building to provide additional stiffness to the structure. Additionally, buckling-restrained axial dampers (BRAD) are installed within the external frames to serve as dissipative bracing for the seismic protection of the building. These dampers act as easily replaceable "seismic fuses" that concentrate the plasticity and damage during an earthquake.

The effect of the system, with or without other energy efficiency interventions (replacement of the obsolete gas boilers and provision of geothermal heat pump) was evaluated for a case study of a residential building in Bari, Southern Italy, built in 1981. In terms of energy efficiency, significant reductions in energy consumption can be achieved, while the PV panels can produce 51% of the energy consumption for hot water without any additional redevelopments, and up to 100% of the energy consumption of the heat pump for heating and cooling, in case of their installation. Moreover, the seismic behaviour, evaluated through FEM, shows that the exoskeleton can reduce the top displacement of the building by 41.3% and 36.8% in its weaker and stronger directions, respectively.

4.3 Integrated interventions on existing building envelopes

Given the large vulnerability and high energy transmittance of the vertical building envelope, particular attention in combined renovation strategies is paid to envelop elements (e.g. infill walls or structural masonry). By intervening on the existing elements, a structure can be strengthened while additionally reducing its energy consumption through thermal insulation. Different avenues can be identified in the literature such as the application of: (1) composite materials; (2) in-situ constructed panels/walls, (3) prefabricated panels (cement-based or timber-based), or finally (4) the local strengthening of the existing openings integrated with upgrading of the old fenestration. In the case of all envelope strengthening solutions, the increase in base shear capacity, as well as in shear forces acting on the existing frame, mean that a careful evaluation of the foundation and frame elements needs to be carried out, as these elements may need to be strengthened additionally.

4.3.1 Strengthening of existing infill or masonry walls with composite materials

Rather than constructing new building elements, an integrated structural strengthening and energy retrofitting intervention can be applied to the existing building envelope. For unreinforced load-bearing masonry walls or infill walls of RC-frame structures, strengthening can be applied to achieve a reliable structural response. From a seismic point of view, a retrofit intervention on the infills prevents the sudden brittle failure of unreinforced masonry (URM) walls or infills and hence permits utilising their compressive strength and stiffness in the overall behaviour of the structure. Several strengthening solutions using composite materials have been tested and a summary is provided in (Pohoryles and Bournas, 2020b). These range from textile-reinforced mortars (TRM), fibre-reinforced polymer sheets, which are bonded using epoxy raisins (FRP) 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.

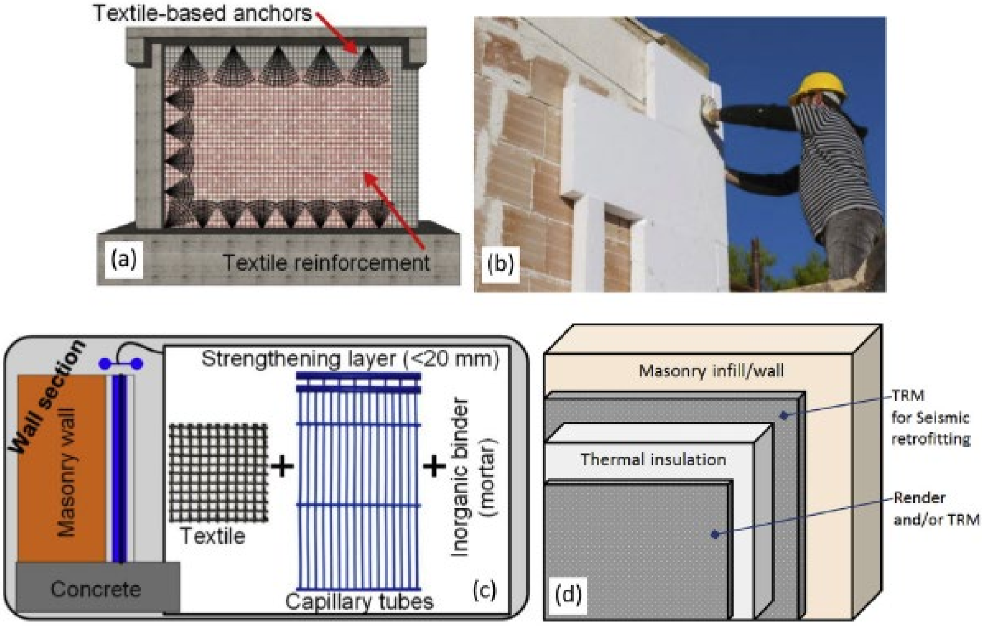
TRM have gained much attention in recent years for their use in integrated seismic and energy retrofitting of building envelopes (e.g: Triantafillou et al., 2017; 2018; Bournas, 2018; Gkournelos et al., 2020; Kouris et al., 2021; Pohoryles and Bournas, 2021). It is made of (high strength) lightweight textile fibre reinforcement (e.g.: carbon, glass or basalt bidirectional fibres with open-mesh configuration) combined with cementitious mortars. The application of TRM to concrete or masonry building envelopes is characterised by low invasiveness (as a plaster layer), and relatively easy workmanship, as shown in **Figure 24**. Next to its relatively low cost, TRM has advantages of a high strength-to-weight ratio and high compatibility and bond with concrete and masonry substrates (Kouris and Triantafillou, 2018; Koutas et al., 2019). Additionally, compared to FRPs, TRM has better performance in terms of fire resistance (Kapsalis et al., 2019; Triantafillou et al., 2017) and behaviour at high temperatures (e.g.: Tetta and Bournas, 2016; Raoof and Bournas, 2017a; Raoof and Bournas, 2017b; Cerniauskas et al., 2020).

Figure 24. TRM application procedure: (a) dampening of surface; (b) first layer of mortar; (c) textile application; (d) patch textile application; (e) wrapping of the specimen; (d) final finishing.

Source: Koutas and Bournas, 2019 (CC BY 4.0)

As shown in **Figure 25**, TRM can be easily applied together with different thermal insulation solutions (e.g. as summarised in **Table 2**). Bournas (2018) 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 25. 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

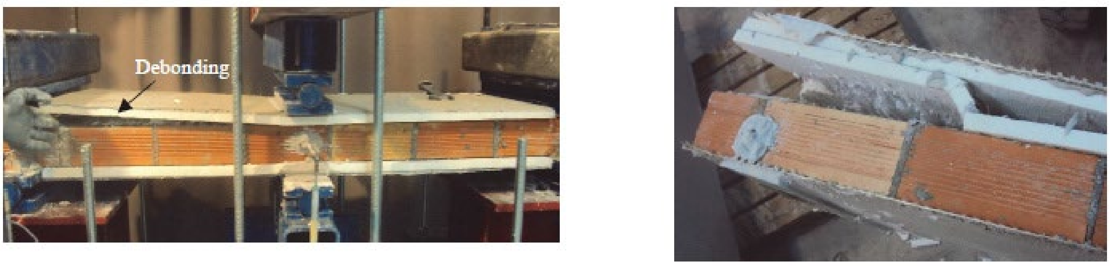


Source: Bournas, 2018 (CC BY 4.0)

In terms of experimental investigations, combined TRM and foamed polystyrene and foamed cement insulation for the integrated retrofitting of masonry walls were tested by Triantafillou et al. (2017; 2018). Various configurations of insulation and TRM placement were tested on masonry wallettes subject to out-of-plane loading and their fire behaviour was evaluated as well, by performing out-of-plane tests after their exposure to temperatures up to 870°C (Triantafillou et al., 2017). It was found that the behaviour of masonry walls retrofitted with TRM and foamed polystyrene was superior to that of TRM-strengthening alone, mainly due to the increased lever arm. TRM alone increased the out-of-plane strength by 170%, whereas the combined systems ensured an increase between 200% and 340%. In terms of out-of-plane deformation capacity, the combined system was again more effective than the TRM alone, with improvements by 140-145% (Karlos et al., 2020). The failure mode was textile rupture when the TRM was placed directly on the masonry surface, but debonding was observed when placed externally, on top of the thermal insulation (e.g. similar to **Figure 26**). For those specimens which were first subjected to fire, the placement of the textile below the insulation layer proved to be more effective, provided that the insulation material is fire-resistant.

Figure 26. Debonding at the insulation–masonry interface (a) one layer; (b) two layers of insulation.

(a) (b)



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

This retrofitting system was also found to be highly effective in improving the in-plane behaviour of masonry walls (Triantafillou et al., 2018). The retrofitting system was applied in the form of two- or one-sided jacketing and with the insulating panel either on the outer face or between the TRM and the masonry. It was concluded that the exact positioning of the TRM and the insulation material does not play an important role in the in-plane response, as long as proper bonding between the different layers is achieved. Placing the TRM reinforcement above the insulation layer does not seem to compromise the activation of its fibres. Single-sided configurations resulted in only a slight reduction of their efficiency, compared to the symmetrically reinforced specimens. This is a crucial benefit in a real-world retrofitting scenario, as it allows to perform all the work from the outside of the structure, drastically reducing the cost and the disruption of building occupancy.

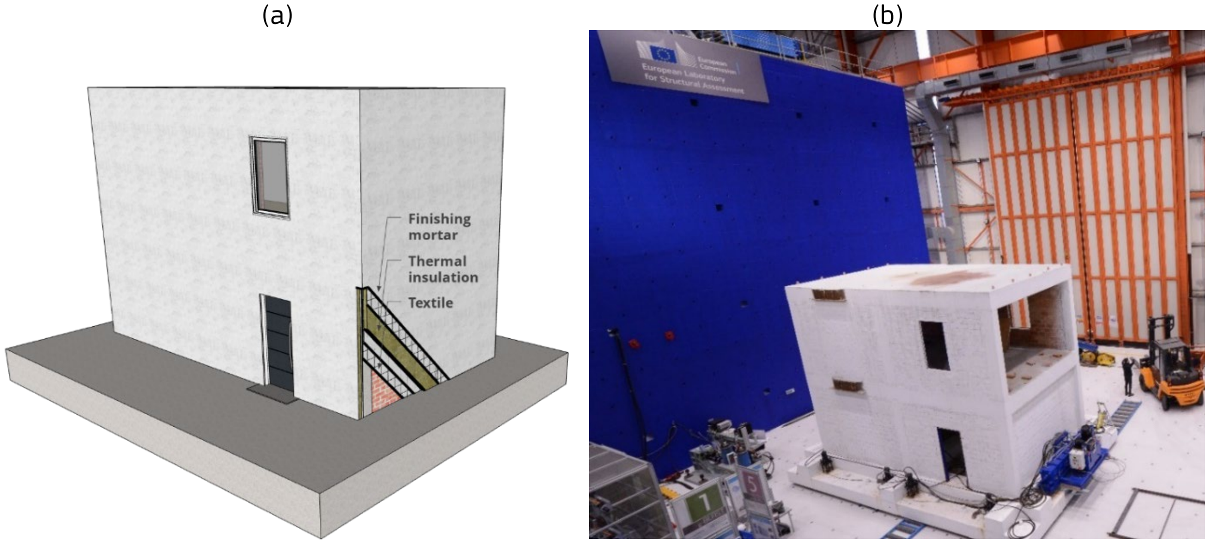
As part of the same effort, Gkournelos et al. (2020) tested the effect of in-plane damage on the out-of-plane behaviour of masonry walls insulated with foamed polystyrene and strengthened with TRM. Wall specimens were subjected to diagonal compression first, to induce some initial in-plane damage to them. Then, they were tested in monotonic, three-point bending until their failure. Next to an improved in-plane behaviour, the out-of-plane capacity of the retrofitted specimens was significantly improved. In accordance with previous research, the experiments showed that the in-plane behaviour of retrofitted walls is not affected by the position of the TRM when the insulation is bonded adequately to the masonry substrate. Again, the out-of-plane behaviour of the combined seismic and energy retrofitted specimens (TRM+polystyrene) presented a better behaviour than the TRM retrofit alone due to the increased lever arm. In the insulated specimens, debonding of the insulation was observed, which indicates that the quality of the insulation-to-masonry connection imposes an upper limit to the amount of force that can be transferred to the textile.

Along the same lines, Giaretton et al. (2018) also performed in-plane testing on clay brick masonry wallettes strengthened with different G-TRM configurations, including a specimen with an external thermal insulation layer. The application of TRM to the tested wall panels improved their performance by avoiding the brittle failure observed on all un-retrofitted specimens. Diagonal shear tests were performed for four single-sided TRM-only strengthened walls, which presented a peak diagonal load on average 43% higher (with results between +18 and 82%) than the as-built one. For the specimen retrofitted with TRM applied on top of an external insulation layer, a similar crack pattern and an increment of peak diagonal load (+75%), i.e. in the same range of the single-sided TRM-only strengthening, were obtained. It is worth noting that the application of the TRM layer above the external thermal insulation layer included screw-anchors to secure it to the masonry wall.

This type of solution is also investigated on a full-scale building currently undergoing testing at the JRC's ELSA laboratory within the iRESIST+ project (Pohoryles and Bournas, 2021), as shown in **Figure 27**.

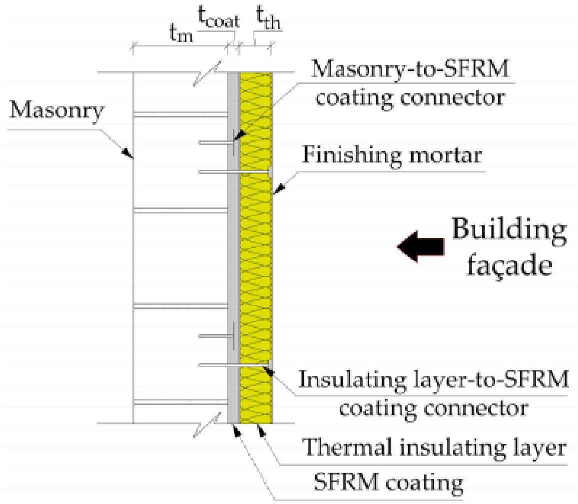
Figure 27. (a) iRESIST+ combined retrofitting with TRM and thermal insulation. (b) Prototype structure at the ELSA facility of the European Commission, Joint Research Centre (JRC).

(a) (b)



Very recently, the use of Steel Fibre Reinforced Mortar (SFRM) combined with thermal insulation materials was explored by Facconi et al. (Facconi et al., 2021) as shown in **Figure 28**. SFRM consists of steel fibres randomly dispersed in a thin layer of mortar (ECC) and the proposed thermal insulation consists of either (1) a 50mm thick panel made of needled fibreglass and silica aerogel, or (2) an 80-120mm thick layer of wood fibres. These can be adjusted depending on the local energy upgrading requirements. A detailed BEM of a case study residential masonry building from the 1960s in L'Aquila, Italy, was carried out. With the retrofit, the U-value of the walls can be improved from 1.038 W/(m^2K) to 0.242 to 0.335 W/(m^2K) for the aerogel panel or wood fibres, respectively. With the latter, more cost-effective solution, a reduction in energy needs by 17.1% was achieved. Additional replacement of the windows would lead to savings up to 29.3%. The seismic improvements were verified using FEA, highlighting an improved displacement capacity, five times larger than the demand at the LSLS of the Italian NTC2018 guidelines (MIT, 2008).

Figure 28. Steel Fibre Reinforced Mortar (SFRM) combined with thermal insulation.



Source: Facconi et al., 2018 (CC BY 4.0)

TRMs by themselves have a low insulating capacity, hence the need to couple with thermal insulation to achieve a combined seismic and energy retrofitting. Several studies[3] have however investigated the modification of mortars to yield better thermal properties. Borri et al. (2016) investigated the mechanical and thermal properties of different thermally insulating mortars with embedded glass fibre grids as a strengthening system for solid brick masonry wall panels. Different mortars made of natural materials (hydraulic lime, aerial lime, limestone sand and lightweight mineral aggregates) were tested, achieving reduction in thermal transmittance (U-values) of the masonry walletes between 34 and 45%. The addition of the glass fibre grid improves the thermal properties of the mortar layer by 12-15% due to additional air trapped in the mortar layer. Still the lowest achieved U-value (0.71 W/(m²K)) would not be sufficient for the most stringent guidelines. In diagonal shear tests (see **Figure 29**) the retrofitted specimens using stronger (non-thermal) mortars achieved increases in shear capacity up to 115%, while only modest increases (0.8-13.35%) were obtained with thermal insulating mortars. However, the use of a mortar with moderate strength and thermal properties (hydraulic-based lime with the addition of granules of cork), shows potential, with an increase in strength between 17.6 and 28.5%.

Figure 29. Diagonal compression testing of masonry walls with thermal TRM.

Source: Borri et al., 2016 (CC BY 4.0).

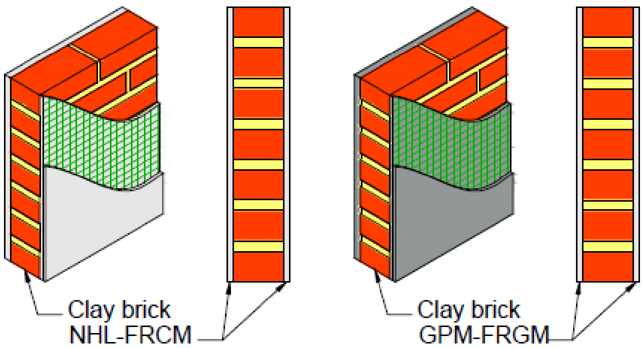
In terms of developments in mortars, recent work by Coppola et al. (2019) investigated the use of lightweight cement-free mortars, in which a GFRP mesh is embedded, for the structural retrofit and energy upgrading of low-quality masonry walls. A cement-free alkali-activated slag-based mixture is compared to a traditional Portland-free mortar in terms of mechanical and thermal properties for different lightweight aggregate contents. For the novel mortar, a 28-day compressive strength equal to 8 MPa, compared to 2–2.5 MPa for the traditional mortar. In terms of thermal conductivity, a value of 0.35 W/(mK) was achieved, which is about 75%

[3] Some of these studies do not address specific systems for combined structural and energy retrofitting, but still have their own merit by offering the potential to be used in mortar-based systems.

lower than for the traditional mortar (1.30 W/(mK)). While the results are promising, the performance of the FRP-grid strengthened mortar was not yet tested for structural strengthening.

Longo et al. (2020a; 2020b; 2021) have explored the use of lightweight geopolymer-based mortars (GPM) embedded with GFRP mesh to create a fabric-reinforced geopolymer matrix (FRGM) for their use in concurrent structural and energy retrofitting. A comparison of the novel FRGM with commercially available FRCM systems using a Natural Hydraulic Lime (NHL) mortar was first conducted in terms of thermal and mechanical properties of small samples (Longo et al., 2020a). Due to the use of expanded glass aggregate, the GPM has a 33% lower mass density leading to a reduced thermal conductivity (-73%) compared to the NHL alternative. At the same time, tensile testing FRGM and FRCM coupons showed very similar strength of the two materials (<5%). Finally, masonry panels strengthened with FRCM (**Figure 30**) tested under diagonal compression achieved a higher improvement (+129%) compared to the FRGM (+72%) (Longo et al., 2021). FRGM achieved however a higher reduction in U-value, -46%, from 2.082 W/(m^{2}K) of an existing URM wall to 1.126, while the equivalent FRCM specimen had a U-value of 1.862.

Figure 30. Composites for the combined seismic and energy retrofitting (a) FRCM; (b) FRGM.



Source: Longo et al., 2020a (CC BY 4.0).

While some promising results in terms of reduced thermal transmittance were achieved, to date, none of the solutions integrating fibre grids into thermal mortars can however be used alone to achieve the desired strength and thermal properties for combined seismic and energy retrofitting, hence leaving the need for the addition of thermal insulation materials. For instance, multilayers of retrofitting materials, combining a layer of TRM with an additional thicker layer of high thermal insulation mortars may be a solution to meet both retrofitting needs, as suggested in (Bournas, 2018). Additional thermal performance may be obtained by applying a finishing layer of innovative thermal plasters, which do not improve the mechanical properties of the masonry wall or infill but enhance the energy efficiency. Examples of this include aerogel-based mortars or plasters, reducing thermal conductivities up to 75% (e.g: Buratti et al., 2014; Kim et al., 2013; Ng et al., 2015; Ng et al., 2016) or PCM incorporated mortars (e.g: Cunha et al., 2013; Lu et al., 2019).

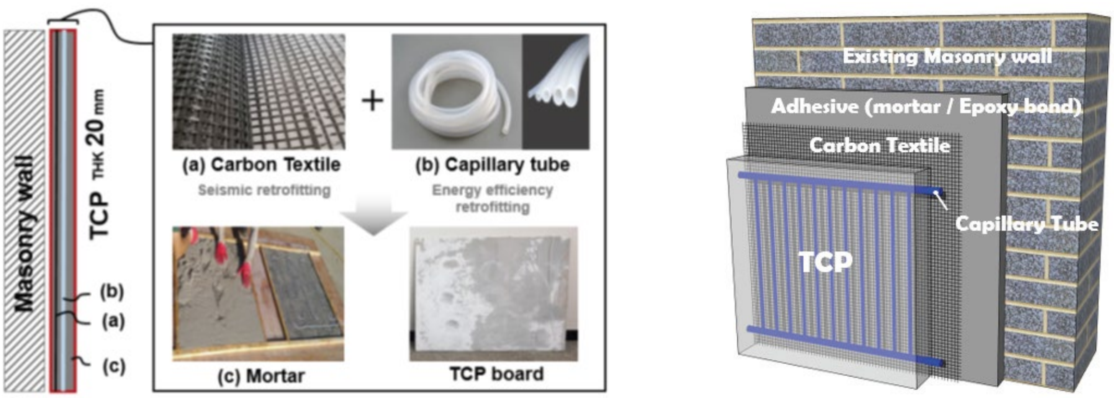
4.3.2 Prefabricated integrated panels

4.3.2.1 Precast cement-based panels

Along the same lines of TRM-based systems, different textile-reinforced precast mortar/concrete panel systems have been proposed in the literature for integrated retrofitting of existing building envelopes. The advantage of precast panels is that they may be applied faster onsite, reducing the time and cost of the intervention. A type of textile-based precast retrofit panel is the TCP, or Textile and Capillary tube Composite Panel (Choi et al., 2020; Baek et al., 2022). Here, capillary tube heating systems are embedded with a carbon textile in a layer of mortar to create a precast panel, as shown in **Figure 31** (a). The TCP retrofit was developed within the international joint research collaboration projects iRESIST+ and SEP+[4] between the JRC and the Korea Construction Engineering Development Collaboratory Management Institute (KOCED CMI). Preliminary cyclic tests on concrete-block masonry walls with and without TCP showed an increase of 42% in strength and a 40% increase in deformation capacity for the retrofitted walls. Further structural and thermal tests are currently ongoing.

[4] 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

Figure 31. TCP combined seismic and energy retrofitting panel, (a) composition; (b) application on a masonry wall.



Source: Choi et al, 2020 (CC BY-NC 3.0).

Finally, another recently proposed panel system for combined structural and energy retrofitting is that of Sousa et al. (2021), who developed multi-function sandwich panels comprising thin faces of recycled steel fibre reinforced micro-concrete (mortar) and a polystyrene core (XPS or EPS). The connection between different layers is achieved by glass fibre reinforced polymer connectors. This initial study presented the mechanical characterisation of the different components of the sandwich panel (faces, core, connectors). The strength of the individual components and different connectors was found to be satisfactory. The impact of different polystyrene typologies was found to have an impact on the mechanical (shear) performance of the panels and extruded polystyrene with irregular/rough surfaces performed the best. Further tests of the sandwich panel within RC frames subjected to pseudo-dynamic cyclic loads are currently ongoing and will shed light on their possible application in seismic-plus-energy retrofitting.

4.3.2.2 Timber-based technologies

In the framework of sustainable and resilient construction, wood 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 CO_2 manufacturing (Asdrubali et al., 2017; Nocera et al, 2018). The use of wood, and in particular 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 strategies. CLT panels (**Figure 32**a) are solid wood elements consisting of three, five or seven stacked crosswise (typically 90 degrees) layers of softwood boards, bonded together with structural adhesive. OSB (**Figure 32**b) is a type of engineered wood similar to particle boards, formed by adding adhesives and then compressing layers of wood flakes in a specific orientation. These components are lightweight and can be easily prefabricated and applied to buildings, e.g. using mechanical fasteners or timber frames. Moreover, timber-based panels have been used successfully for the seismic upgrading of masonry (e.g.: Guerrini et al., 2021; Miglietta et al., 2021; Giongo et al., 2021) and RC buildings (e.g.: Sustersic and Dujic, 2014; Stazi et al., 2019).

Figure 32. a) Section of a CLT panel, b) detail of OSB panel.

(a)

(b)

Source: (a) Guo et al. (2017) - (CC BY 4.0); (b) Zanuttini et al. (2020) - (CC BY 4.0).

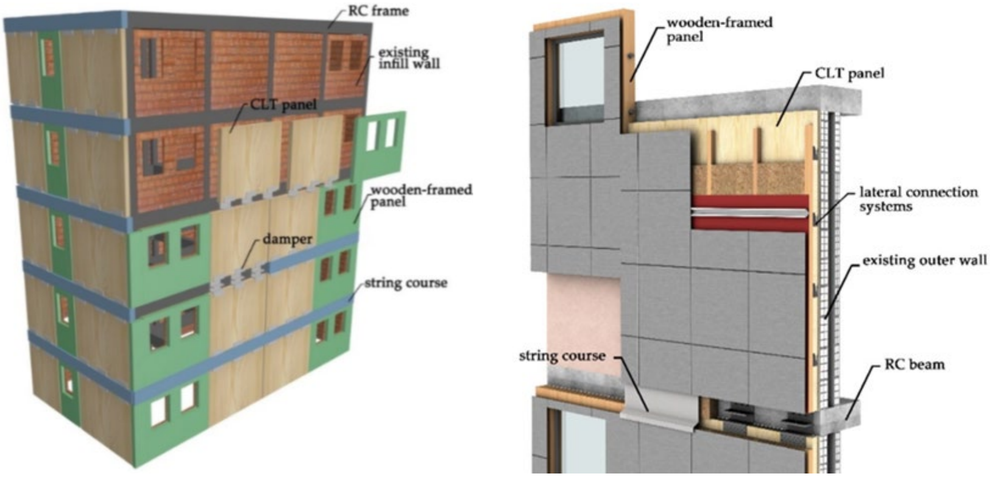
Multiple studies have proposed the use of CLT and OSB panels as an integrated retrofitting strategy for either RC buildings (Stazi et al., 2019; Margani et al., 2020; Smiroldo et al., 2021) or load-bearing masonry buildings

(Dalla Mora et al., 2015; Valluzzi et al., 2021; Busselli et al., 2021). Stazi et al. (2019) demonstrated the concept of using CLT infill walls for the seismic and energy retrofitting of RC buildings. The proposed retrofit increases the overall lateral stiffness of the RC frames, hence reducing lateral drift, and, at the same time, achieving an energy efficiency upgrade through the addition of an external insulation layer (PUR panels) directly connected to the 3-ply CLT panels and/or by leaving a vented air gap. Initial mechanical characterisation (diagonal compression tests) of the CLT infills (Stazi et al., 2019) has shown that they are considerably stronger (τ_{max} = 4.46 MPa) compared to typical masonry infills (0.66 MPa) and even when compared to masonry infills strengthened with expanded steel plates (3.54 MPa) (Cumhur et al., 2016).

Margani et al. (2020) proposed the use of prefabricated CLT panels for a combined energy, seismic and architectural renovation of existing RC buildings (**Figure 33**). The CLT panels are connected to masonry infill walls of RC frame buildings using seismic energy dissipation devices which reduce drift demands, thus damage during earthquakes. Note however that this system is still in a conceptual phase and has not yet been tested. The use of dissipative steel connectors for CLT panel retrofits has however been shown to improve the seismic behaviour, by reducing the energy transmitted from the CLT panel to the frame (Marchi et al., 2020; Latour and Rizzano, 2017). The effect of the system on the energy efficiency of an RC building was evaluated for a case study in Southern Italy (**Figure 34**a). Through the integration of bio-based insulating materials (e.g. hemp, cellulose, sheep wool etc) within the panels, combined with new high-performing windows and a ventilated façade system, the U-value of the walls can be reduced by nearly 80% (from 1.25 to 0.29 W/(m^{2}K)). BEM were performed and showed a decrease in overall annual energy demand for heating and cooling up to 56%. Finally, within the context of the New European Bauhaus, it is also interesting to note that the proposed retrofitting solution can be combined with different modern cladding materials on the outer face of the panels to modernize the architectural look of the building, as shown in **Figure 34**.

Figure 33. 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.

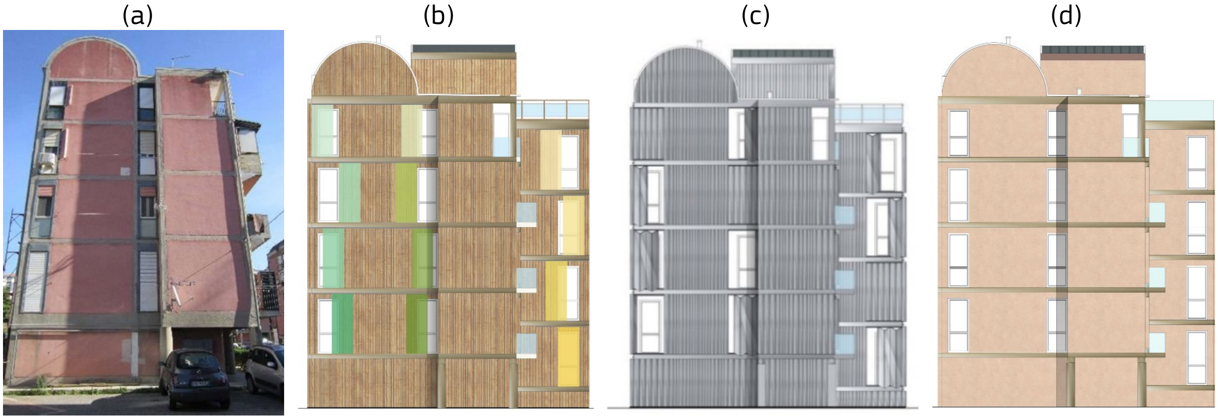
(a) (b)



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

Figure 34. Proposed external cladding for CLT panel retrofit of case study building: (a) current state; (b) cladding with wooden boards; (c) metallic sheets; (d) plaster.

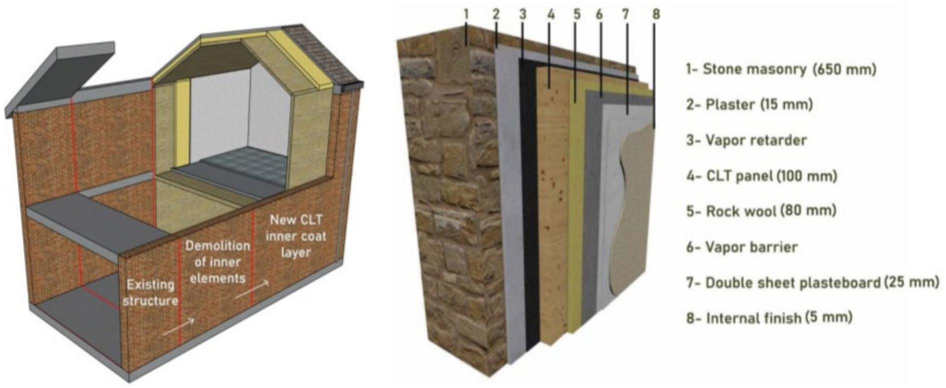
(a) (b) (c) (d)



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

Finally, a very unusual CLT-based retrofitting technique is presented by Valluzzi et al. (2021), in which the building is entirely refurbished from the inside as shown in (**Figure 35**a). The so-called Nested Building retrofit involves the removal of the internal elements and the insertion of an inner coat layer made by CLT panels, integrated with thermal insulation layers (as shown in **Figure 35**b). Such a retrofit would be suitable to preserve the external envelope of buildings (e.g. in the case of historical value). Through numerical modelling, it was demonstrated that this technique could achieve an increase in global stiffness with a reduction of in-plane displacements (20-30%). In addition, CLT combined with a rock-wool layer (8 cm) ensure a reduced U-value of: -49% for solid clay brick masonry, -69% for hollow brick masonry, -87% for stone masonry.

Figure 35. (a) Nested Building retrofitting strategy; (b) Layers of retrofit with CLT timber and thermal insulation attached to the masonry wall.

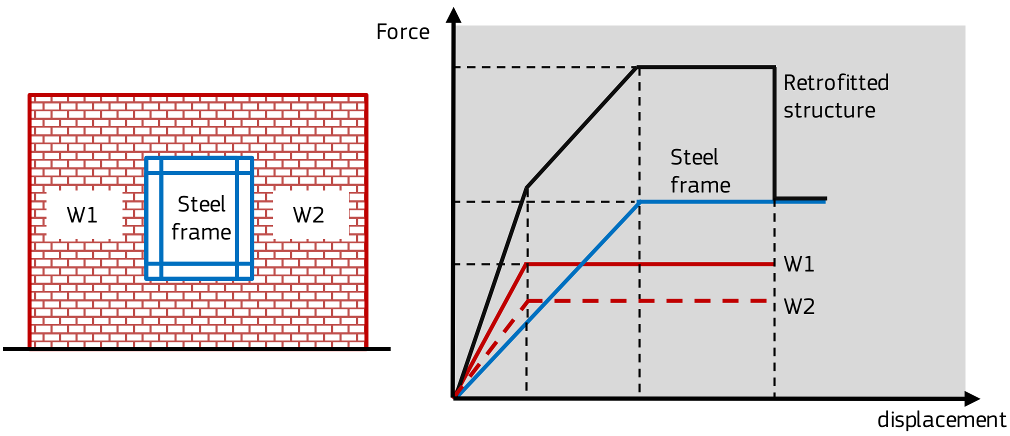


Source: Valluzzi et al., 2021 (CC BY 4.0)

4.3.3 Strengthening of openings with structural frames with fenestration replacement

To retrofit masonry walls with openings (e.g. for windows or doors), introducing a steel frame for strengthening the opening (**Figure 36**) and replacing old windows and doors with new ones is particularly suitable for URM buildings. The seismic behaviour of the existing structure can be improved if the steel frame is adequately linked to the masonry and designed considering the original stiffness of the wall. The steel frame around the opening can of masonry walls. 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, as shown in **Figure 36**. Originally, this type of intervention was developed to address the (frequent) cases where new openings are created in masonry walls and aimed to restore (partially) the loss of stiffness and strength caused by the new openings (Billi et al., 2019). The use of a structural steel window frame has been recently tested for individual masonry wall specimens (Proença et al., 2019), which lead to significant increases in the deformation capacity (+25%), the peak strength (+ 40%), and cumulative dissipated energy (+ 147%). Similarly, Oña Vera et al. (2021) have experimentally and numerically verified, showing that the in-plane lateral load and the displacement capacity of a wall without opening can be restored.

Figure 36. Lateral resistance of a wall with steel frame intervention.



Source: Based on Vinci, 2018

The implementation of ductile steel frames for already existing openings, even when not rigidly connected to the surrounding wall, has recently been considered as a retrofit technique (Caliò and Occhipinti, under review) for vulnerable load-bearing masonry buildings. For a numerical case study of a school building, costs and downtime periods for structural window frame retrofit are shown to be reduced compared to other retrofit solutions. At the same time, the new window frame is proposed to be applied with the complete substitution of fenestration. Improvements in energy efficiency and structural performance can hence be gained in an integrated approach, by coupling the structural window frames with a window replacement with low-emissive and airtight ones[5]. The reader is referred to references in Section 3.2.1.3 for an overview of modern window replacement options.

An alternative to the structural steel window frame solutions may be the use of timber-glass prefabricated panels (see **Figure 37**) which could work as windows or infills (e.g.: Ber et al., 2013). Hybrid CLT and load-bearing laminated glass façade elements have been tested under cyclic loading, with encouraging results in terms of lateral load-carrying capacity, deformation capacity and energy dissipation (Žarnić et al., 2020). The glass elements are made of two-ply laminated semi-tempered glass (10 mm thick each). Beyond their mechanical properties, the energy efficiency of this kind of component has been experimentally evaluated with promising results (Rajčić et al., 2020). Even though these elements frames are not yet used in the seismic and energy rehabilitation of masonry buildings, they show a high potential in future applications.

Figure 37. Hybrid CLT and load-bearing laminated glass façade elements.

Source: Ber et al., 2013 (CC BY 4.0).

4.4 Replacement of envelope elements with better performing materials

Strengthening interventions on existing non-structural envelope elements, e.g. for masonry infills, may often not be feasible in practice or not economically viable (e.g. due to very poor quality or damage of the existing envelope). In such cases, the replacement of envelope elements may be a valid alternative, despite being significantly more invasive compared to the retrofitting interventions carried out on the (external) side of existing infill walls. This is particularly the case when a retrofit of the frame would require intervention on structural elements and hence partial demolition of the existing infill walls, the construction of a new wall, and the related loss of finishing and instalments on the previous wall, making a full replacement an economically viable alternative. This subsection addresses RC or steel framed structures for which the building envelope (e.g. infills/panels) can be replaced, however such a replacement is not applicable to masonry buildings as their envelope is made by load-carrying components (the walls).

In the case of replacement of the envelope, recent research has focused on the development of elements that can provide at the same time adequate seismic resistance and improved energy performance. In terms of the seismic performance, this can mean (1) an increased stiffness and strength of the new infills, or (2) increased deformability of the frame by reducing interactions between infill and RC frame. For energy performance, approaches can include the use of new and more energy efficient elements (e.g. brick units and/or mortar) for the wall construction, and/or the application of insulating layers on top of the new wall.

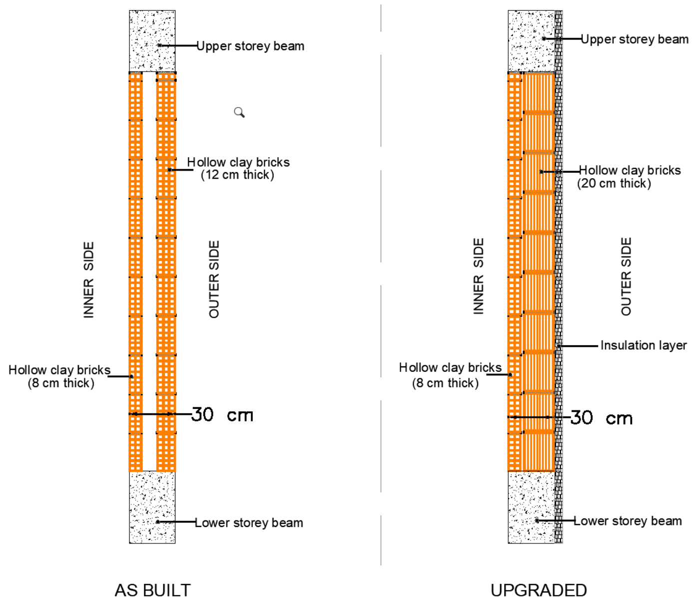
4.4.1 Replacement with stronger and stiffer elements

Masi et al. (2017) proposed the replacement of the outer infill layer in a typical double-layer infill (with a gap) with thicker and more resistant clay bricks, having also lower thermal transmittance, adding also an external insulation layer, as shown in **Figure 38**. This approach, developed in the framework of the latest Italian research

[5] Note that the replacement of fenestration may need to be combined with new mechanical ventilation equipment.

projects (DPC-ReLUIS), aims to make a typical 1970s Italian RC residential building, designed to gravity loads, satisfy the requirements of the current Italian standard on energy efficiency and obtain a benefit in terms of seismic capacity. For a case study, a reduction in energy consumption of 40% was demonstrated, (energy class improvement from F to D). Additionally, the new infill panels led to an increase in base shear capacity (+25%) and stiffness (+58%). Moreover, the spectral pseudo-acceleration corresponding to the life safety limit state (SLV in the Italian design guidelines) was evaluated for the as-built structure (Se (T_0) = 0.110g), and the partial replacement of infills allowed to increase the value of Se (T_0) to 0.168g, thus recovering the seismic deficit for zones with medium seismic hazard. For a location of high seismicity, replacement of the infills alone was found not to be sufficient (Manfredi and Masi, 2018).

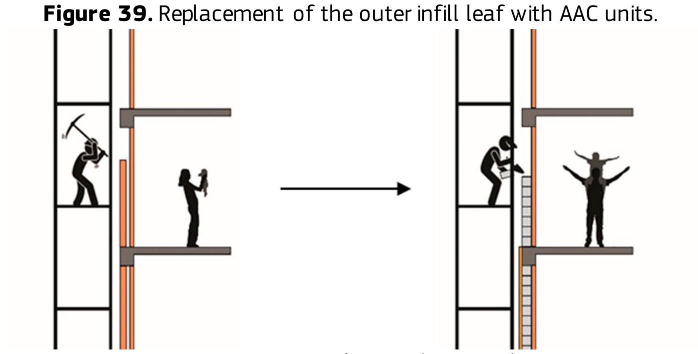
Figure 38. Replacement of the outer infill leaf with better performing clay units.



Source: G. Santarsiero based on Masi et al. 2017.

A similar approach was taken by Artino et al. (2019), who proposed the replacement of the external layer of double-leaf infill walls, with high-performing Autoclaved Aerated Concrete (AAC) blocks and thermal insulation. Again, this solution aims to reduce the disruption of the building occupants by operating mainly from the outside of the building. The use of 20 cm thick AAC blocks to replace thin clay bricks provides an increase in stiffness and strength, as the AAC blocks are nearly three times stiffer (E = 3000 MPa vs 1200 MPa) and over four times stronger (f_m = 5.35 MPa vs 1.2 MPa). At the same time, the energy performance is improved, as the U-value of the new infill wall with additional 4 cm insulation is significantly lower (0.343 W/(m^{2}K)) compared to the initial one (U = 1.11 W/(m^{2}K)). The analysis of a case study, namely a typical 1970's Italian residential RC building, showed that the proposed technique can increase the PGA at the SLV limit state by 57%, from 0.091g to 0.143g. Note however that such an increase might not be sufficient for moderate and high seismic areas. Through detailed BEM, it was calculated the total energy demand for heating and cooling was reduced by 38% and 27%, respectively.

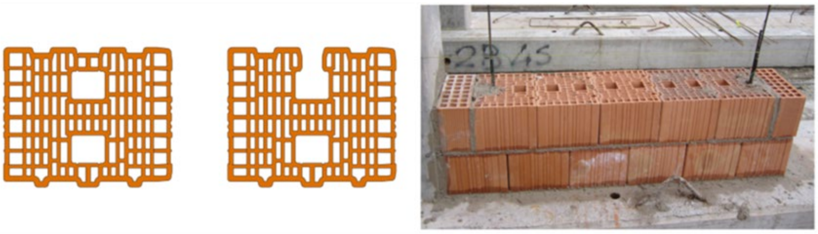
Figure 39. Replacement of the outer infill leaf with AAC units.



Source: Artino et al., 2019 (CC BY 4.0).

Another approach to strengthen and stiffen the structure is by replacing the existing unreinforced masonry infill walls with steel reinforced masonry. The new infills can be constructed from thick perforated clay units (i.e., with thickness > 25–30 cm) which provide a more adequate thermal and acoustic performance, as shown in **Figure 40**. An experimental evaluation of such robust clay masonry infills by da Porto et al. (2020) has shown reduced in-plane damage and increased in-plane strength (+26%), which, in turn, led to an increased out-of-plane capacity of the reinforced specimens. Finally, CLT panels can be used to replace masonry infills providing seismic and energy upgrading (see section xx).

Figure 40. Replacement of existing envelope by reinforced masonry (RM) infill walls.



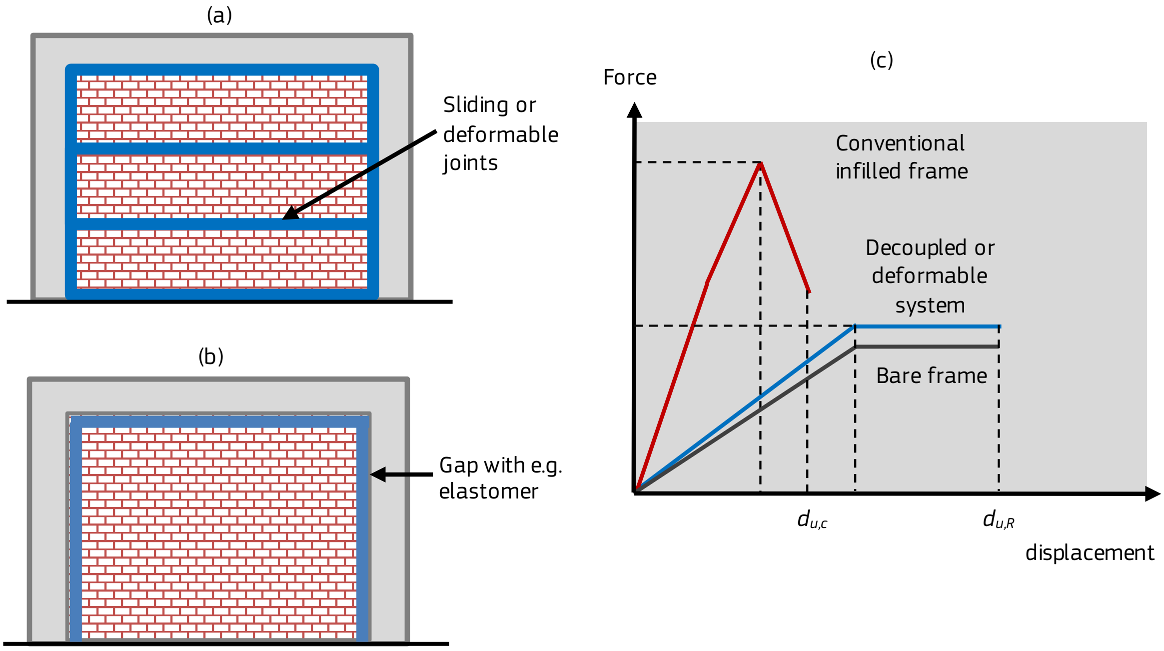
Source: da Porto et al., 2020 (CC BY 4.0).

Overall, through infill replacement, a single intervention can achieve both seismic and energy upgrading. By replacing only the external layer of the masonry infills, the level of disruption is relatively low. Note, however, that through the replacement of the infills with stiffer ones, the maximum base shear that the building can sustain will increase and therefore the effects on the foundations must be verified, with the possible need for strengthening. Moreover, the insertion of stronger masonry infills can cause interaction and brittle failure of the column ends, therefore, local strengthening interventions are suggested in combination. For instance, steel, FRP or TRM confinement may be used to overcome this problem.

4.4.2 Replacement with deformable or decoupled infill walls

An alternative approach, which avoids the issue of increased base shear or potential damage to the RC frame, is to increase the frame deformability by replacing the existing infills with infills that are (1) fitted with deformable or sliding joints or (2) decoupled from the frame, as illustrated in **Figure 41** (a) and (b), respectively. A more ductile behaviour with higher deformability, closer to a bare frame structure, can be achieved as shown in **Figure 41** (c). The use of 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) were proposed within the European FP7 project INSYSME (da Porto et al., 2016).

Figure 41. Replacement with decoupled infills: (a) using sliding joints; (b) provision of a gap; (c) influence on frame behaviour.



An example of a system with horizontal sliding joints is the one tested by Morandi et al. (2018). The masonry panel is split into horizontal subpanels, which are separated by plastic sliding joints positioned at the mortar bed joints as in **Figure 41** (a). Modern clay brick units were chosen in order to provide not only satisfactory structural properties but also adequate thermal and acoustic characteristics and durability. The system was tested in-plane under cyclic loading and compared to a traditional infill wall. It was shown that damage to the infills was significantly delayed and a considerable increase in deformation capacity could be achieved without significant cracks in the masonry. Damage corresponding to the Damage Limitation Limit State (DLS) was observed at 3.0% drift compared to 0.5% in the traditional wall system.

Vailati et al. (2018) proposed a mortar-free infill system, intending to reduce the stiffness of the infill panels and enhance their deformation capacity, in which the brick units are connected through are connected through joints made from recycled plastic instead of mortar layers. Additional vertical plastic strips are connecting the units to prevent out-of-plane collapse. The joints are designed to also hold the thermal insulation, e.g. an EPS panel, giving the system an adequate U-value of 0.19 W/(m^2K). The in-plane performance of the panels was experimentally verified, in which displacements nearly double the limits set out by the Italian NTC08 code could be safely sustained (Vailati et al., 2014).

An alternative approach to reduce infill-frame interaction and hence control damage is to uncouple the infill panel through the interposition of a layer of soft and deformable materials between the frame and the masonry enclosure, as in **Figure 41** (b). The use of cellular polyethylene strips has been explored to isolate infills from steel (Tsantilis and Triantafillou, 2018a) or RC frames (Tsantilis and Triantafillou, 2018b). The system was shown to eliminate frame-infill interaction and prevent damage for small to medium levels of drift. With increased in-plane drifts, i.e. for larger earthquake intensities, the cellular materials are fully compressed, activating the infills and increasing the strength and stiffness of the tested frames. Similar results were obtained by Marinković and Butenweg (2019), who placed elastomers along the sides and top of the infill walls, constructed with highly thermally insulated clay bricks. To avoid out-of-plane failure of the infill, lateral shear anchors were provided.

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. Brick units filled with more advanced materials, such as aerogels (see **Figure 42**) have also been proposed and were found to achieve a very low U-value of 0.157 W/(m^2K) for a wall, but come at a relatively steep additional cost of 1000€/m^2 of the building envelope (Wernery et al., 2017). Filling masonry unis with PCMs, which can be used for passive thermal control (see Section 3.2.1, has also been proposed in the scientific literature (e.g.: Kant et al., 2017; Saxena et al., 2020), with reported heat flux reductions up to 10%.

Figure 42. Aerogel-filled masonry units.

Source: Wernery et al., 2017 (CC BY 4.0).

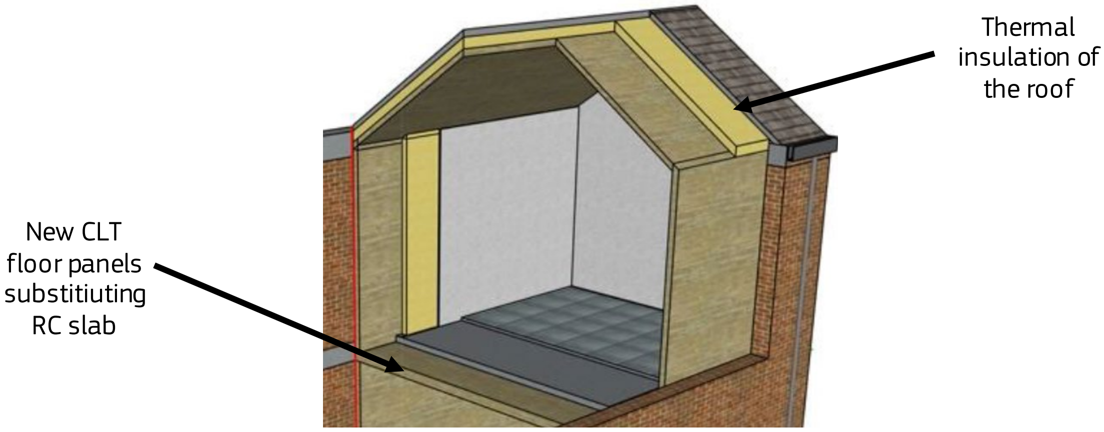
Another research avenue for the replacement of infill materials would be the use of novel composite bricks made with sustainable, fully recyclable materials, having good resistance and insulating properties. Examples include natural materials, such as papyrus (Karim, 2019), Kenaf or oil palm cellulose (Razab et al., 2019; Mocktar et al., 2020), or the use of waste materials from industrial production (El-Naggar et al., 2019; Doğan-Sağlamtimur et al., 2021), which both reduce the environmental footprint of the newly constructed infill walls. However, the structural and seismic behaviour of such composite bricks is generally not (yet) investigated, leaving room for further research.

4.5 Interventions on floor diaphragms and roofs

In the seismic behaviour of a structure, horizontal diaphragms have the task of transferring the horizontal actions to the resistant elements (Žegarac Leskovar and Premrov, 2019).. In masonry buildings particularly, the floor and the roofs are typically made of timber joists and wooden planks or one-way steel beams with large flexural deformability and low in-plane stiffness, for this reason, stiffening interventions are often necessary (Gattesco and Macorini, 2008). Timber joists may be less typical, but can also be found in early RC buildings (Montuori et al., 2017), as well as other vulnerable types of floors, such as hollow-tile floors, having no RC slab or with slabs not well connected to the floor beams, where the in-plane stiffness is not guaranteed (Basiricò and Cottone, 2009). From a thermal point of view, as with walls and windows, also the horizontal elements of older structures have U-values far higher than those of modern buildings, as was presented in **Figure 4**.

Concerning the concepts of compatibility in combined retrofitting in Section 4.1, interventions on horizontal elements would appear to be particularly compatible, in terms of their invasiveness, spatial overlapping and scale of application. Still, *specific* technologies for the integrated retrofitting of roofs or floors have not been sufficiently investigated. In the Nested Building retrofit (Valluzzi et al., 2021), presented in Section 4.3.2.2, 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 (see **Figure 43**). Similarly, the existing roof structure can be demolished and rebuilt or be complemented by an internal CLT+thermal insulation layer.

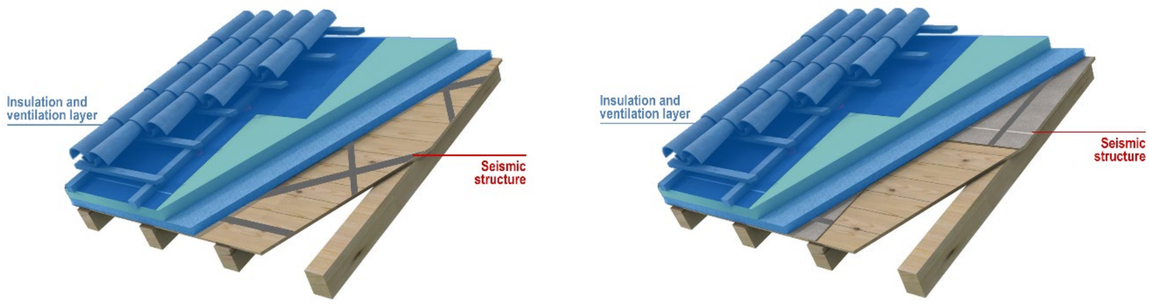
Figure 43. Nested building approach – detail of floor and roof improvements through CLT panels and thermal insulation.



Source: Adapted from Valluzzi et al., 2021 (CC BY 4.0)

For roofs, Giuriani et al. (2016) proposed a technique for the recovery of historic wooden roofs. The solution, similar to the schematic view presented in **Figure 44**, is based on the construction of a thin folded 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.

Figure 44. Schematic views of the thin-folded shell combined with ventilating layer for existing wooden roofs.



Finally, Basiricò and Enea (2018) suggested the combination of structural intervention on the roof through steel hooping with the use of insulation panels for energy upgrading the existing historic structures. This retrofitting strategy, amongst others, is explored in more detail in the next section on the considerations for cultural heritage buildings.

4.6 Considerations for Cultural Heritage buildings

Traditional and historic buildings constitute an important part of the European building stock. Cultural heritage buildings (CHB) encompass a wide range of the EU's built heritage which includes the architectural heritage of a country (e.g. Brutalist concrete architecture of the 1950s and 60s), historic masonry town centres (e.g. in Portugal, Italy), etc. While the number of historic buildings is estimated to range from 1% to 5% of the building stock, depending on the region, traditional and historic buildings together account for between 10% and 40% of the building stock, depending on the region and age considered (Webb, 2017). As an example, residential historic buildings in Italy (built up to 1919) represent about one-fifth of the national built heritage (Moschella et al., 2018).

Masonry buildings comprise the big majority of heritage buildings (historic and monumental) having a high cultural value, for which however not all the seismic and energy upgrading techniques are suitable. In fact, among design requirements for historic buildings, the respect of the heritage value of the building must be considered. Therefore, conventional design choices adopted for ordinary buildings may not be suitable for historic ones (Moschella et al., 2018). The design process according to an integrated approach for seismic and energy upgrading requires careful consideration of the cultural constraints of the specific building which often lead to local interventions with reduced impact (Besen et al., 2020).

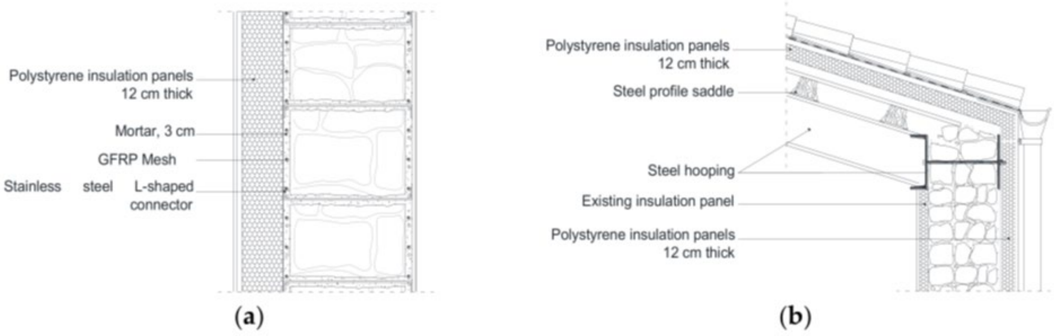
In the last decades, the heritage value of historic buildings was often considered as an obstacle to the implementation of energy-efficient interventions, resulting in the exemption of historic buildings from energy efficiency programs in several European countries (Webb, 2017). Traditionally, more focus has hence been given to the structural improvement of historic buildings, while guidance on their thermal performance upgrade has been an object of little concern. For example, many times energy retrofitting includes the adoption of energy-efficient windows (able to simultaneously mimic original windows without historic value and present a high energy efficiency), not interfering with the historical character of buildings, and underfloor and ceiling insulation solutions, but ignoring walls, which may originate important energy losses through the building envelope (Besen et al., 2020). Also, active systems (heating/cooling solutions) tend to be preferred to passive approaches (e.g. thermal insulation, which may affect the vapour permeability of structural elements).

As with all types of buildings, the energy retrofit of historic buildings cannot be isolated from seismic risk mitigation actions, particularly in Southern Europe where seismic hazard must be accounted for. Recently, the European framework for action on cultural heritage SWD 2018/491 (DG EAC, European Commission, 2019) highlights the importance of safeguarding the built heritage, as well as ensuring their energy efficiency. The integration of seismic and energy retrofit of historic buildings allows to preserve them against hazards related to seismic events and climate change, while the use of suitable materials, systems and methods may minimize the impact of the interventions on the heritage value, typically applied to the building envelope (Besen et al, 2020). Ascione et al. (2017) proposed a multidisciplinary approach to structural and energy performance assessment of historical buildings, highlighting the potential for combining energy efficiency interventions with local structural interventions for the general safety of the building. A series of recent multidisciplinary methodologies combining seismic and energy improvements and respecting the heritage value of historic buildings have been proposed based on relevant case studies following a step-by-step approach, e.g. De Berardinis et al. (2014), Basiricò and Enea (2018), Moschella et al. (2018), Negro, D'Amato, and Cardinale (2019), Besen et al. (2020), Güleroğlu et al. (2020). Different technical solutions were adopted in each building to protect the heritage value and promote cost-efficient solutions. In most cases, the combination of active and passive energy-efficient measures with seismic strengthening seems to deliver the most effective solution considering simultaneously seismic, energy and cost performance. Each building has particular features (e.g. in terms of typology, geometry, morphology and construction technology) and poses specific problems, thus demanding a tailor-made solution.

For buildings with cultural and historic value, particular attention needs to be given to defining which retrofit technologies are compatible. For instance, a framework for energy efficiency solutions was developed by De Berardinis et al. (2014), who investigated masonry structures in minor historical centres of the Abruzzo region in Italy, with a focus on preserving the cultural heritage represented by local vernacular construction. As the region was heavily affected by seismic damage (2009 L'Aquila earthquake), consideration to the seismic safety is also taken for the renovation options. While their work does not consider combined seismic and energy retrofitting, it sees the seismic damage as an *opportunity* to restore and reconstruct the historic masonry building fabric considering improved energy and structural performance of the existing vertical building elements. The study provides an *evaluation matrix* relating different masonry types to various compatible solutions and scoring the solutions according to their cost and energy efficiency.

This evaluation matrix was used by Basiricò and Enea (2018) to define different combined seismic and energy retrofitting schemes for four case study buildings in the historic centre of Enna, Italy. The combination of interventions on the external walls and the roofing of the structures was found generally to be the most appropriate. Examples of the suggested retrofitting for walls and roofs are shown in **Figure 45**. For the walls, polystyrene insulation panels are combined with a glass-fibre mesh embedded in a mortar (equivalent to TRM). This may be combined with an intervention on the roofs, e.g. connection of the existing roofing with the masonry through tie-rods or internal hooping through iron profiles (as shown in **Figure 45**b). Additional insulation panels can be applied on top of the steel hooping to improve the thermal performance of the roof. For the case study, historic masonry buildings improvements in seismic risk class from F to E were obtained, while the energy class could be improved by 3 classes from G to D, with reference to the Italian seismic risk and energy efficiency classification frameworks.

Figure 45. Detail of seismic and energy interventions on (a) vertical walls and (b) roofing.



Source: Basiricò and Enea, 2018 (CC BY 4.0).

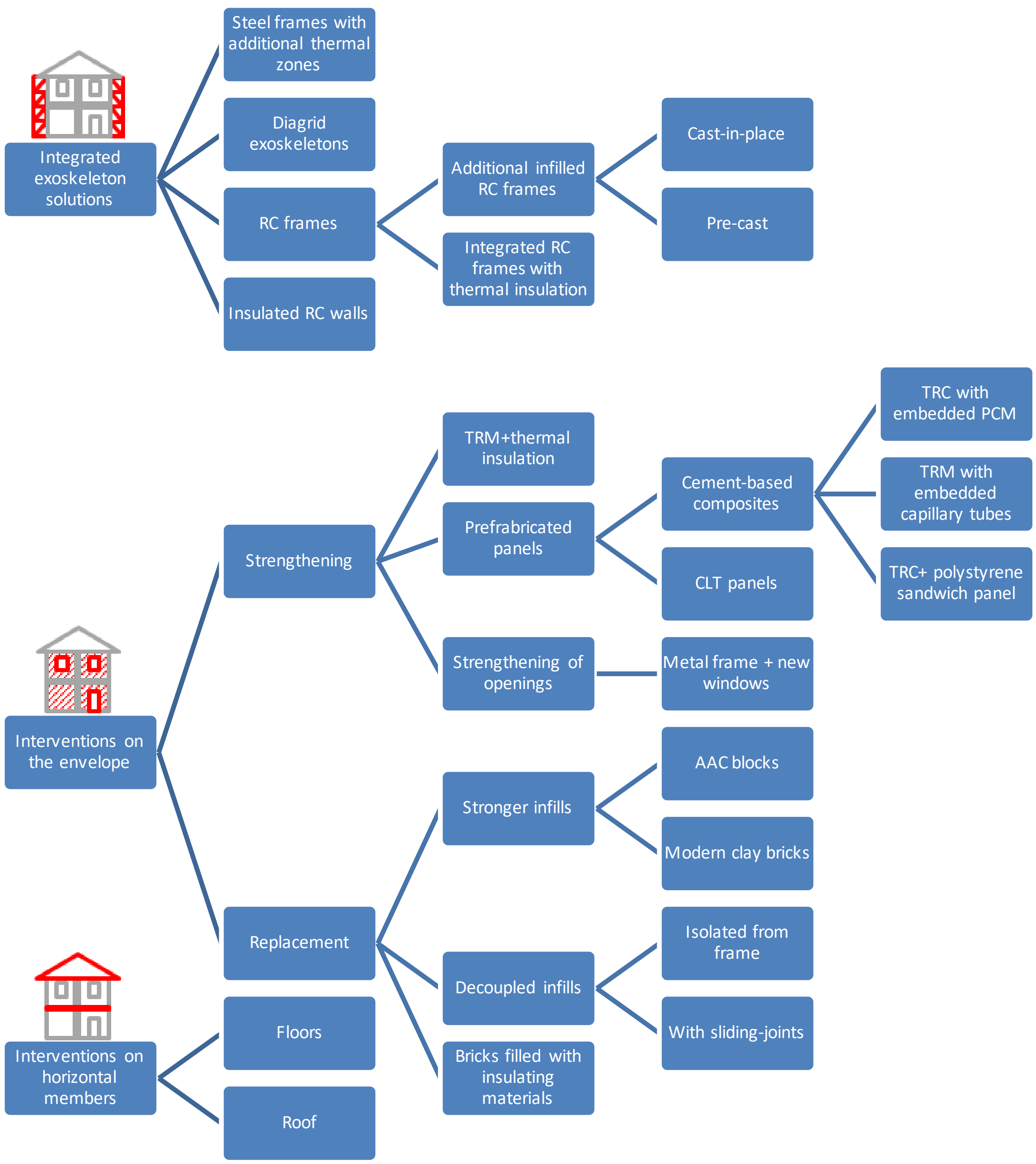
Additionally, in several studies on TRM-based solutions (see Section 4.3.1), particular attention was given to the upgrading of historic masonry structures, by testing the use of lime-based mortars. For instance Coppola et al. (2019) presented the development of an innovative plaster, that can be used for the structural and energy upgrading of historic stone masonry buildings. Due to the strong deterioration of the walls of such structures, compatibility with the poor quality of the substrate needs to be ensured. In any case, when the external façade of the historic building cannot be changed, such TRM applications may still not be possible, or may only be applied from the inside (if applicable).

Negro et al. (2019) suggested the use of non-invasive methods for the integrated structural and energy retrofitting of historical buildings. An Italian building, built in 1540, was considered in their study, which included its energy assessment and retrofitting with kenaf plates. The authors also suggested the use of Kenaf/PLA (Poly-Lactic Acid) composites for the structural upgrading of very old masonry walls. Finally, the proposed Nested Building retrofit (Valluzzi et al., 2021) presented in Section 4.3.2.2, was also devised to be compatible with historic structures, as the intervention is carried out fully from the inside, fully preserving the appearance of the external façade.

5 Analysis of retrofit technologies

Despite research into combined seismic and energy retrofitting being a relatively new field, the previous Section highlighted that several directions have already been explored and different technologies have been proposed and are currently being tested. **Figure 46** aims to provide an overview and categorisation of the identified combined retrofitting 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.

Figure 46. Categorisation of combined retrofitting technologies.



In **Table 4**, different criteria for comparing the retrofit technologies are summarised. These are presented and discussed in more detail in the following sub-sections. The improvements in terms of lateral load capacity, and reduction of U-value, are based on results from the studies presented in Sections 3 and 4. These values are approximate and will depend highly on the actual application of the material used, in particular with regards to the improvement in U-value, which may be higher or lower dependent on the actual thickness of thermal insulation material used. 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…).

Indicative costs of the implementations (including the direct costs evaluated, but excluding any indirect costs such as costs for residents' relocation or business downtime) are presented, based on the evaluation in Section 5.1. 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, while the level of disruptiveness reflects the duration of the intervention, business downtime and the necessity for residents' relocation. These are described and discussed in more detail in Section 5.2. 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 4. Summary comparison of different seismic-plus-energy retrofitting strategies.

	Lateral load capacity improvement	**U value reduction**	**Unit cost of implementation**	**Level of invasiveness**	**Disruptiveness**	**Integration of seismic-energy retrofit** [(4)]
Wall Exoskeleton systems	50-100%	70-80%	250-710 €/sm[(2)]	High	Low	Coupled/ Integrated
Shell exoskeleton	50-100%	70-80%	250-700 €/sm[2]	High	Low	Integrated
Interventions on existing envelope (TRM+thermal insulation)	50-60% in-plane	70-80%	160-270 €/sm[(3)]	Medium	Low if carried out from the external face	Coupled
	300-400% out-of-plane					
Opening strengthening with steel frame + new window	25-50%[(1)]	50-70%	900-1700 €/sm of openings	Medium	Medium	Coupled
Timber or cement-based panels	25-50%	40-85%	350-500 €/sm[(2)]	Medium	Low if carried out from the external face	Integrated/ coupled
Replacing of existing envelope	50-100% in-plane	70-80%	120-150€/sm[(3)]	High	Medium-High	Integrated
	300-400% out-of-plane					
Interventions on floors or roof	10-50 times higher in-plane stiffness	50-60%	200-400 €/sm[(3)]	High	High (Low-medium for roof)	Coupled

(1) This value is highly dependent on the total wall and opening area ratio.
(2) The unitary cost refers to the floor area of the building.
(3) The unitary cost refers to the surface of intervention on the building envelope.
(4) Integrated: the seismic plus energy retrofitting is done by a single element; or coupled: two elements working in parallel.

5.1 Costs

In this section, indicative cost estimations for different integrated retrofitting technologies are presented. The availability of parametric costs related to different techniques for the seismic and energy upgrading of existing buildings would be very helpful in the decision-making process regarding retrofit alternatives for single buildings, as well as for economical cost-benefit analyses for regional analyses of entire building stocks. A number of factors have however to be considered, which significantly limit any economical comparison made between different upgrading solutions. For instance:

- each building has its characteristics, possible defects of construction and/or design, material properties, etc., so that it is difficult to evaluate a retrofit cost without a detailed study based on a deep knowledge of the structure;
- there is a large variability of seismic hazard as well as heating/cooling energy demand based on the specific geographical area across Europe;
- geotechnical characteristics of the site regarding both the seismic (local amplification) and static (load carrying capacity) can strongly influence the extent and the cost required to retrofit the foundation system or to realise new foundations for the added structural systems/elements.

Ideally, comparisons on the cost of interventions should be made based on a life-cycle assessment (LCA) approach, considering all the components involved in the design, construction, maintenance, as well as seismic and energy losses during the structure's lifespan. This latter may be strongly dependent on the considered case study structure and its location. However, based on the information provided in the literature, as well as the Italian construction costs from DEI (2019) and from manufacturers, an approximate estimation of direct costs (i.e., not including secondary costs due to business downtime and residents' relocation) is provided for all of the identified intervention strategies. These costs are provided as wide ranges, in order to capture the variety of possible materials used in different interventions.

Note that the costs all refer to the Italian market, however, it is possible to *estimate* costs in other European countries using the European construction cost index (European Construction Costs, 2021). This important tool is a relative cost indicator that provides an estimate of how construction costs in a given country compare to other countries in Europe. **Table 5** provides the cost index for all EU-27 member states with respect to Italy.

Table 5. Construction costs index compared to Italy.

Country	Cost Index	Country	Cost Index	Country	Cost Index
Austria	107.52%	France	110.94%	Malta	84.99%
Belgium	95.36%	Germany	103.19%	Netherlands	87.58%
Bulgaria	52.00%	Greece	67.78%	Poland	70.07%
Croatia	58.74%	Hungary	56.86%	Portugal	53.75%
Cyprus	64.39%	Ireland	84.57%	Romania	49.56%
Czech Republic	65.27%	Italy	100.00%	Slovakia	55.20%
Denmark	155.27%	Latvia	61.84%	Slovenia	85.44%
Estonia	63.37%	Lithuania	62.71%	Spain	75.32%
Finland	121.80%	Luxembourg	104.89%	Sweden	143.31%

Source: http://constructioncosts.eu/cost-index/

The costs of **exoskeleton** retrofits strongly depend on the materials and the type of exoskeleton. For the energy part, there are many possible design options, rendering an accurate cost estimation impossible. The use of insulating panels is very common, with a range of costs from 10-20 €/m^2 for stone wool panels up to 400-500 €/m^2 for aerogel panels. According to the case studies evaluated in the literature[6], the range of possible costs 250-700 €/m^2 (overall square meter of floor area) for shell-type exoskeleton interventions ranging from insulated RC walls to diagrid shells. For the structural part, in the case of steel-braced exoskeletons most common elements are steel HE sections (4-5 €/kg) and a total cost of 250-350 €/m^2 (overall square meter of floor area) may be appropriate. Ferrante et al. (2018) additionally include the cost of window and HVAC replacement (each assumed 80 €/m^2 of overall square meter of floor area), leading to a total cost of 710 €/m^2 (overall square meter of floor area) for their steel exoskeleton. These costs could however be significantly lower in the case of more material-efficient (e.g. diagrid) steel exoskeletons. On the other hand, avoiding business downtime and residents' relocation in exoskeleton applications allows for minimising secondary costs. Ferrante et al. (2018) estimate a cost reduction of 16.5% due to the avoided residents' relocation. Finally, with steel exoskeleton applications, additional floor space (e.g. for balconies or living space) can be generated, potentially leading to a real estate unit value increase, assumed at 130-180 €/m^2.

When **intervening on existing masonry infills or loadbearing masonry walls**, an accurate estimation of the costs for this retrofitting strategy is not possible without an operational case of study. A substantial amount of the total costs depends on the used materials. TRM retrofitting costs[7] about 70-80€/m^2 for infilled RC frames and about 90-100€/m^2 for load-bearing masonry walls costs while the cost of insulating materials depends on the material, with a range of costs from 10-20 €/m^2 for stone wool up to 400-500 €/m^2 for aerogel panels. Common applications, considering also the labour cost and the installation phase, amount to 160-270 €/m^2 (square meter of building envelope area). Bournas (2018) estimated that combining seismic and energy interventions with TRM and insulating panel application on infill walls can reduce costs by 30%, compared to carrying out the seismic and energy interventions separately, by reducing the labour costs.

In the case of **TRC or TRM-based retrofitting prefabricated panels**, a reduced cost compared to the wet application of TRM+thermal insulation can be assumed, as prefabrication and full integration will lead to reduced labour costs, while the material amounts remain similar. For **timber-based panels**, the costs depend on the thickness of the elements, but generally, CLT panels may cost 80-140 €/m^2, while OSB panels are cheaper (25-80 €/m^2). Additionally, to the cost of the timber panels, it is necessary to add the costs of the thermal insulation, any potential partial demolition, application and finishing; a plausible total cost can be estimated in 350-500 €/m^2 (square meter of floor area)[8]. For the **strengthening of openings** combined with new steel-framed fenestration, the costs clearly depend on the size of openings. For typical sizes (i.e. 90x120 or 120x160 cm) an estimated cost of 750-1000 €/m^2 can be assumed for the structural part and 150-750 €/m^2 for the energy part, depending on the performance of the new fenestration[9].

When considering the **replacement of existing envelope members**, the cost may vary according to the type of masonry materials (units and mortar) used and based on the type of masonry, such as ordinary URM, RM walls, infill walls provided with special devices to increase their ductility and deformation capacity, infill walls provided with special devices to allow disconnecting them from the frame, etc. In any case, a plausible range of cost would be 120-150 €/m^2, taking into account dismantling of the original infill, and construction of a better-quality wall (URM, RM, or simple deformable systems)[10]. In addition to these costs, secondary costs, such as costs due to residents' relocation, business downtime, waste removal should be considered, particularly if the intervention is carried out alone and not in conjunction with other types of structural retrofit on the frame elements.

For **interventions on horizontal diaphragms**, a general evaluation of costs is not possible without a specific operative case because of the different possible combinations of seismic and energy retrofitting solutions described in Sections 3.1.2.1 and 3.2.1.4, respectively. Based on their unitary costs (DEI, 2019), the addition of second wooden planks costs 40-50 €/m^2, FRP-based retrofitting interventions cost 30-50 €/m^2, whereas the construction of a new RC slab can cost 50-60 €/m^2. Typical floor insulation can have a cost between 20-60 €/m^2, while a false ceiling costs 35-90 €/m^2, radiant floor interventions cost 70-150 €/m^2 and a ventilated roof costs 40-80 €/m^2. Overall, a minimum of 200 €/m^2 for interventions of this type, considering also dismantling and waste disposal, may be taken into account. A lower cost may be considered for the structural intervention

[6] Prices estimated based on information in Ferrante et al, 2018 and Martelli et al, 2020, increased to account for the possibility of using other material combinations (e.g.: different thermal insulation panel, different steelwork quantity needed, etc...)

[7] Costs estimated based on DEI (2019), cross-checked with commercial companies selling these materials.

[8] Costs estimated based on DEI (2019) and manufacturer estimates.

[9] Costs estimated based on DEI (2019) and cross-checked with numbers provided by window manufacturers.

[10] Costs estimated based on DEI (2019) and manufacturer estimates, cross-checked with estimates obtained during the INSYSME project.

if this is carried out with steel bracing at the intrados. However, in this case, there is no specific combination with energy retrofit, unless this is carried out by adding new installations within a false ceiling or acting at the extrados, which would, in any case, entail a significant cost of the energy retrofit.

To conclude, it has to be considered, however, that these costs refer to different quantities (overall floor area of the building; the surface of intervention on the building envelope; unitary cost of single substituted element). For the sake of a simplistic direct comparison, it is assumed to apply the different retrofitting strategies to a standard 3-storey building with 200 m^2 (10mx20m) of floor surface, 3 m of inter-storey height, which may be either an RC frame with masonry infill walls or a load-bearing masonry building. The building is characterized by a total floor area of 600 m^2 (plus the roof) and a surface of the external walls of 540 m^2. The presence of 12 windows is assumed per floor (2 for every short side, 4 for every long side), with 1.9 m^2 of opening. In the cost estimation, it is assumed that the combined interventions are applied to all of the external walls and for all the floor levels (except for the ground floor but including 200 m^2 of the roof). In **Table 6** the costs (per square meter of the total floor area of the building) of the different retrofitting strategies are presented. The reader is reminded that this evaluation should be considered preliminary and simplistic. The actual costs will vary substantially for different geometric and structural configurations, seismic and climatic zones, etc. A direct comparison of real case studies would be much more significant.

Table 6. Estimated cost of implementation for a standard building (€/sm referring to the overall floor area).

Type of intervention	Implementation costs [€/m^2]
Steel-braced exoskeleton	250-710
Shell exoskeleton	250-700
Interventions on existing envelope (TRM+thermal insulation)	160-270
Timber-based panels	350-500
Strengthening of openings with steel frame	100-190
Replacement of existing envelope	110-140
Interventions on floors or roof	200-400

5.2 Level of invasiveness and disruptiveness

Another crucial aspect is the level of invasiveness, as well as the disruptiveness of the intervention and associated need for resident relocation. The level of invasiveness is defined as a measure of architectonical and functional impact. In **Table 7**, solutions with lower invasiveness are hence those that affect the character and appearance of the building less. Additionally, the need for new foundations or interventions on existing foundations, as well as the need for demolition works and works from the inside are presented. Finally, the effect on the existing living space (i.e. possible increase in the case of exoskeletons), as well as the disruptiveness, i.e. the need for resident relocation and the impact on usability (business downtime) of the building are also included in **Table 7**. Here, the least disruptive interventions are those related to the construction of new structural elements (outside the existing structure) devoted to absorbing seismic actions.

Table 7. Level of invasiveness and disruptiveness of different seismic-plus-energy retrofitting solutions.

	Level of invasiveness	**Change of external appearance**	**Need for interventions or additional foundations**	**Need for demolition**	**Effect on living space**	**Internal works**	**Business downtime**	**Resident relocation**
Wall exoskeleton	High	Yes	Additional	No	Increase	No	Low	Not needed
Grid-shell or Shell exoskeleton	High	Yes	Additional	No	None	No	Low	Not needed
Interventions on existing envelope	Medium	Typically	Possible intervention	Partial	None (Reduction if done from the internal face)	Possible	Medium if carried out from the external face	Not needed if carried out from the external face
Timber or Cement-based panels	Medium	Typically	Possible intervention	No	None	Possible	Low if carried out from the external face	Not needed if carried out from the external face
Strengthening of openings with steel frame	Medium	Limited	No	Partial	None	Yes	Medium	Needed
Replacing of existing envelope	High	Yes	Possible intervention	Yes	None	Typically	Medium-High	Needed
Interventions on floors or roof	High	No	Possible intervention	Yes	None (Possible increase in the case of attics)	Yes	High (Low-medium for roof)	Needed (not always needed for roof)

The complete modification of a building's façade makes **exoskeleton interventions** the most highly invasive of the investigated solutions, causing the highest architectonical impact. For this reason, this kind of retrofit intervention is not suitable for heritage buildings. Nevertheless, especially in the case of post-war RC buildings, this can be considered an important benefit of exoskeletons, as they may be used as an architectural renovation tool, improving the aesthetics of the building façades, and allowing the construction of additional living spaces, balcony and new stories.

Moreover, despite their invasiveness, exoskeletons being built entirely from the outside of the structure minimises the disruption to occupants, reducing business downtime and potentially avoiding relocation of the residents. However, this also depends on the possible need for interventions on the structure itself at the connections to the exoskeleton which transfer the forces between building and exoskeleton (e.g. frame elements or floors). In the case of exoskeleton solutions, additional foundations are built in the perimeter of the structure, which reduces disruption to occupants: Still the need for excavation works around the building often require service suppliers (water, gas, electricity, telephone and internet operators) to be consulted, and this possibly causes delays and related disruption (Santarsiero et al., 2021).

Construction time and labour intensiveness can also be considered lower for exoskeletons than for all other interventions if standardised connections, modular elements and dry solutions (in the case of steel or precast concrete exoskeletons) can be employed. Using precast RC elements or steel sections speeds up the intervention works with a further reduction of indirect cost and discomforts for users. Compared to the cast-in-place RC frame or RC wall solutions, precast auxiliary frames have a much lower level of disruptiveness. Hence, this technique may be particularly suitable for public buildings, such as hospitals, which require retrofit strategies with very low impact on its use, as it is often impossible to move inpatients to other facilities. Additionally, there is an absence of demolition works and related waste, again reducing occupancy disruption if careful work planning is made. 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, minimising building downtime also during the maintenance process.

The invasiveness of **interventions on the existing envelope** depends on the operational strategy. Although intervening on two sides may be more effective, TRM strengthening can generally be applied on the external side of existing infill walls only (which also prevents the out-of-plane failure of infills), thus allowing to avoid downtime and residents' relocation and improving cost-effectiveness. 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. Depending on the initial seismic performance of the building and the quality of masonry, a double-sided intervention could however be needed. In these cases, or in the case where the external appearance of the structure cannot be modified, total or partial relocation of residents cannot be avoided. In addition, thermal bridges are formed, reducing the energy efficiency of the intervention. Intervening on the internal side also generates a loss of gross floor surface.

Similarly, the level of invasiveness of interventions using **timber-based or precast panels** is dependent on the possibility to carry out the works from the outside of the structure. In any case, the use of prefabricated panels reduces the onsite work and labour time, hence also the associated downtime. However, it has to be considered that the effectiveness of the intervention depends on the reliability of the structural connections between panel system and the original structural elements. Particularly for masonry structures, if the substrate quality is very low, there may be the need for increasing the masonry wall compactness or quality by applying additional strengthening materials. This would entail a prolonged duration of the intervention, increased costs, and higher levels of invasiveness and downtime, depending on the selected ancillary intervention.

In the case of any strengthening or stiffening intervention of the existing envelope presented above, another aspect to be kept in mind is that according to the type of intervention, the forces acting at the existing building foundations, or those acting at the frame nodes, may require additional strengthening interventions, i.e. increasing building works and disruptiveness.

Strengthening interventions on openings may be regarded as suitable and of a medium level of invasiveness if window replacement is anyway needed to reduce energy losses from the building envelope. 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. However, if a sequential approach is adopted, where the building undergoes partial and consecutive downtimes where the works are concentrated, the timespan of resident relocation and business downtime can be reduced significantly. Another aspect to be considered is the thickness of existing wall elements compared to available steel profiles that can be reasonably used to frame the opening. 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.

Replacing existing infill walls with more (seismic and energy) efficient elements allows to improve the performance of the building to any desired level. Nevertheless, this strategy is very invasive and disruptive, with resident relocation being (typically) necessary and business downtime being substantial. The impact of the retrofit may be less significant when it is possible to replace only the outer leaf of a masonry infill as considered in some interventions. In either case, the replacement of masonry infills requires the demolition of at least one layer of masonry infills, with related disturbance and vibrations, which additionally generates a great amount of waste, which is very often not recyclable due to the age of the original material. Moreover, the possible presence of building systems inside the external infill's leaf would require more invasive works.

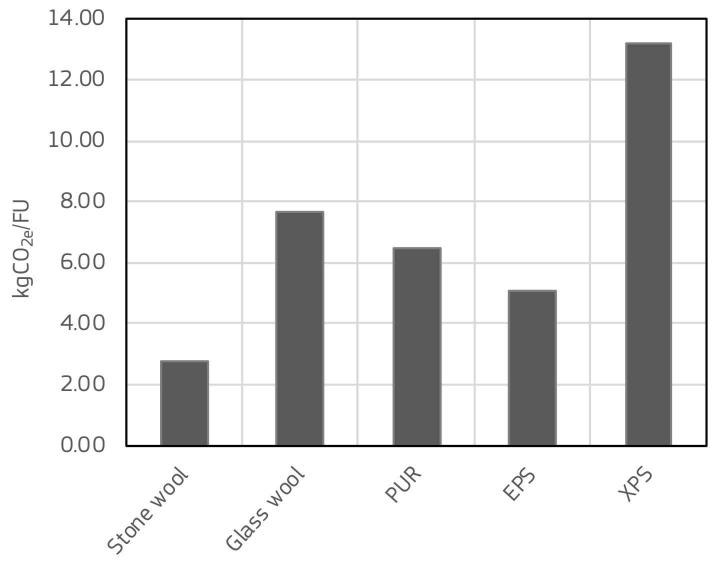
In addition, if one replaces an original weak infill with a more robust one (with considerable in-plane and out-of-plane capacity), the increase of lateral stiffness can produce not only a decreased deformability of the frame, but also an increased seismic demand to the frame. This eventual increase of forces at the RC frame nodes and foundation level hence needs to be taken into account, with the added need for interventions on the RC frame elements and/or on the existing foundations. Note that this would not apply in the case the infill is replaced with decoupled infills. The disruptiveness of this intervention is however less significant if interventions on the RC frame are already foreseen (e.g. in the case of low joint shear capacity or an inadequate hierarchy of strengths between beams and columns), and this entails a partial or complete dismantling of the existing infill walls. In such cases, the disruptiveness and invasiveness of infill replacements may be justified as it additionally will improve the overall building quality and indoor comfort.

Finally, interventions on the **horizontal elements** of a building, particularly on intermediate floors, are associated with a high level of invasiveness and disruption. When the intervention is carried out on the extrados, it is generally necessary to remove the existing floor layers and finishing, and in more recent structures, it is generally necessary to completely reconstruct the installations (either electric system or plumbing). When working on the floor intrados, it is generally needed to remove existing finishing layers, but the work can be also carried out directly on the structural elements (e.g. in the case of wooden or steel floors). In any case, 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 these reasons, business downtime is considerable. Regarding interventions on the roofs, downtime may be reduced and the relocation of residents may be avoided, depending on the presence of an attic floor that divides the roof structure from the inhabited space and according to the type of intervention, i.e. if the intervention is carried out above the existing structural layers or not.

5.3 Environmental impact

In addition to insulating properties, it is very important to assess the environmental impact of the combined retrofitting solutions, based on the equivalent embodied CO_2 emissions produced e.g. during manufacturing, transport and/or installation, up to the entire life-cycle of construction materials or components (Grazieschi et al., 2021). The cradle-to-gate embodied carbon ($kgCO_{2eq}$) of typical insulation materials is shown in **Figure 47** per Function Unit (FU), where one functional unit represents the amount/thickness of material required to achieve a U-value of 1 $W/(m^2K)$.

Figure 47. Embodied carbon of various insulating materials per Functional Unit (cradle-to-gate).



Source: Elaborated using data from Schiavoni et al., 2016

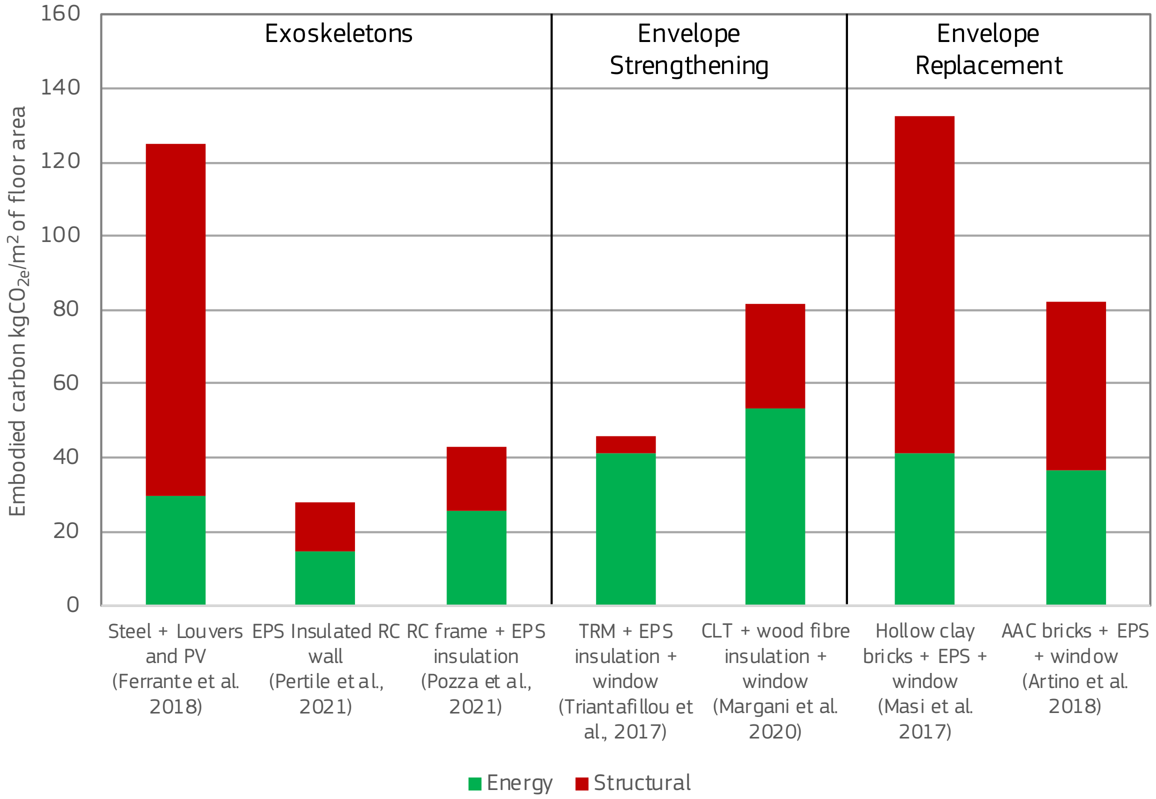
For a better eco-efficiency of an intervention, particular attention should hence be paid to the choice of materials, both in terms of thermal insulation and structural retrofitting. Moreover, it is important to minimise the use of raw materials and to reduce waste production. In **Figure 48**, a very simplified assessment of the environmental impact of the materials used within the different integrated retrofitting schemes is presented. The embodied carbon (cradle-to-gate) of the materials **only**[11] is calculated based on the quantities (e.g. thickness of panels, sizes of sections) suggested in the individual publications reviewed in Section 4. The amount of material is then attributed to the same three-storey RC structure used for the cost calculation in Section 5.1 and presented as a normalised value per m^2 of floor area. Details of the calculations and data used can be found in the Annex. The embodied carbon values of the different materials are taken from the latest version of the ICE database (V3.0 – 10 Nov 2019)[12]. A distinction is made between the embodied carbon of the materials used for structural and energy purposes. Note that for the strengthening and replacement solutions, the assumption of a window replacement (as proposed for these interventions) is also taken into account, assuming

[11] Embodied carbon of transport, construction works etc is hence **not** taken into account

[12] ICE (Inventory of Carbon & Energy) database (https://circularecology.com/embodied-carbon-footprint-database.html)

the use of triple-glazed windows (0.9x1.2m). For the steel exoskeleton, a combination of photovoltaics, green walls and louvers is assumed to cover the envelope in equal quantities.

Figure 48. Simplified assessment of the cradle-to-gate embodied carbon for the materials used in different integrated retrofitting schemes.



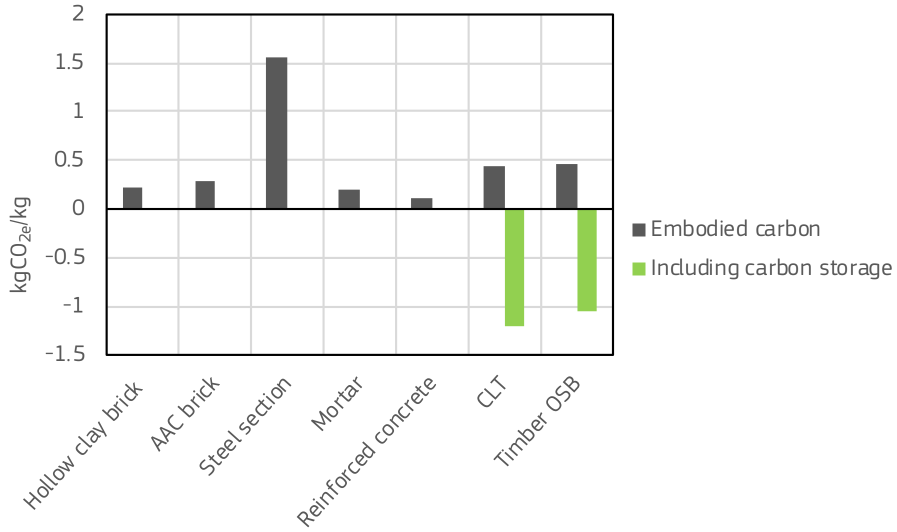
Source: Based on embodied carbon data from the ICE (Inventory of Carbon & Energy) database V3.0 – 10 Nov 2019

The numbers in **Figure 48** should be taken with care and are for illustration purposes only. For instance, the amount of strengthening and insulation provided by the different solutions may not be (and is not) equal. Overall, next to the environmental impact of the individual materials used, in a full assessment, the embodied carbon of transportation and retrofit construction (along with potential demolition and waste) would also need to be considered, however, these are very country and site-specific. Note that the level of seismic and energy improvement amongst the different techniques included in **Figure 48** is different, and therefore the simplified analysis presented should be seen as illustrative only, and not comparative among the integrated techniques.

For steel exoskeletons, the embodied carbon of the structural system is the largest of all assessed systems. This may however be reduced if future technologies to decarbonise the steel industry are taken into account. For a recent assessment on how to address CO_2 emissions of the steel industry, see Somers (2022). Additionally, the potential use of recycled materials should be considered, as well as the reduced demolition waste compared to retrofitting solutions on the envelope, horizontal diaphragms or replacing the envelope. Furthermore, it is also important to think about the full life cycle of the building and the retrofit intervention. In the case of steel exoskeletons, an important environmental consideration is the possibility of recycling or reusing elements at the end of service life or the possibility of easy repair of individual fuse elements in the case of an earthquake. This may improve significantly the embodied carbon of steel exoskeleton interventions. In the case of RC frame exoskeleton interventions, the use of a precast system could bring similar advantages, from an LCA point of view, as it makes the elements potentially demountable. In case of seismic damage, the precast members can be replaced individually and at the end of life, the elements can be removed without demolition and potentially be re-used.

Additionally, for wooden materials the CO_2 capture and store capacity should also be considered, which would significantly lower the embodied carbon of CLT or OSB compared to other construction materials like concrete and steel, as shown in **Figure 49** (Hammond and Jones, 2008)[13]. This was however not considered in the comparison above.

Figure 49. Embodied carbon of different construction materials (with and without carbon storage).



Source: Based on data from the ICE (Inventory of Carbon & Energy) database V3.0 – 10 Nov 2019

Finally, next to the carbon footprint of the materials, it has to be considered that combined seismic and energy retrofitting can have a mutually beneficial impact from a life-cycle perspective. For instance, the potential effects of combined (energy and seismic) interventions have been introduced in LCA frameworks by Belleri and Marini (2016). The environmental impact of seismic risk on the energy refurbishment of a RC building case study in Italy was evaluated using annual embodied equivalent CO_2 emissions (ECO_2e) as metric. It was found that seismic risk was playing a very significant role in the outcome of the actual annual CO_2e. With increasing site seismicity, the annual expected ECO_2e associated with the seismic risk is a large percentage of the CO_2e associated with the operational energy. In the case of high seismicity, it was shown that annual operational CO_2 emissions after energy retrofitting of the building increase from 10% to 87%, with and without structural retrofitting carried out in combination with the energy refurbishment, respectively. Therefore, in such sites, retrofitting objectives should account for both the reduction of energy needs as well as the seismic exposure.

5.4 Economic benefits of combined retrofitting

The applicability of any retrofitting scheme depends highly on its cost, particularly if it is to be employed on a large scale. Likewise, the proposed integrated structural and energy schemes need to be financially reasonable, otherwise, their adoption will be delayed considerably. Such economic feasibility studies have already been completed and their most important findings are outlined in the following paragraphs.

The need for a common approach in assessing the efficiency of the seismic and energy resilience of an existing structure was introduced by Calvi et al. (2016). Towards this direction, they proposed the use of a common financial decision-making metric called **Expected Annual Loss** (EAL). This is practically the cost of the structure in one year, usually defined as a ratio with the denominator being its total value. The total EAL can be broken down into the parts that contribute to it, the most important of which are the EAL due to energy consumption (EAL_E), and the EAL due to seismic losses (EAL_S) for countries located in seismic areas. Therefore:

$$EAL \approx EAL_E + EAL_S$$

$$EAL_E = \frac{mean\ annual\ energy\ cost}{total\ building\ value} \quad EAL_S = \frac{expected\ annual\ seismic\ loss}{total\ building\ value} \tag{1}$$

Estimating the EAL_E is a straightforward task, which consists of evaluating the energy performance of the building at hand and translating it to an annual cost. On the other hand, the estimation of seismic loss is a more complex task, during which a building-specific **loss exceedance curve** must be defined. The construction of such a curve has to take into account the structural integrity of the building, the seismic risk of the site and an

[13] ICE (Inventory of Carbon & Energy) database (https://circularecology.com/embodied-carbon-footprint-database.html)

applicable loss model. Various case studies were performed, showing that the retrofitting integrated approach is the most advantageous.

Leone and Zuccaro (2016) employed macro-scale simulations of natural hazards' impact to assess the efficiency of seismic and energy retrofitting strategies for whole communities. The region of L' Aquila (Italy) was modelled, as it was recently hit by a major earthquake (2009) and numerous data were available. Three mitigation scenarios were considered: (a) seismic improvement, (b) seismic improvement along with energy retrofitting that would achieve 25% less consumption, and (c) equal to (b) but with 50% less energy consumption. It was found that the economic impact of not taking any action was heavier than applying mitigation strategies and that the mitigation scenario (c) would result in the fastest payback time.

Addressing mainly masonry structures, Sassu et al. (2017) proposed a new performance parameter approach for the assessment of combined seismic and energy retrofitting solutions. They suggested the following generalized rule for this combined assessment:

$$g_R(c_R\Delta R)^{a_R} + g_D(c_D\Delta D)^{a_D} + g_U(c_U\Delta U)^{a_U} + g_M(c_M\Delta M)^{a_M} = P \qquad (2)$$

In the formula above, P is the performance parameter which can be the investment, maintenance, environmental or even social cost of the refurbishment, normalized to the respective initial value. Then, this cost is broken down into four different parts, two structural (R for resistance, D for drift) and two energy-related ones (U for thermal resistance, M for energy inertial mass); ΔR, ΔD, ΔU, ΔM denote the respective, relative increments of those characteristics. The c_i coefficients represent weights of the structural or energy requirements and depend on the area of the structure; for example, c_R can be defined as the ratio between the PGA at the location of the building and the maximum PGA of a country. Lastly, g_i and a_i are adaptive coefficients. Using such a formulation, it is possible to evaluate the efficiency of retrofitting techniques in terms of their structural and energy performance in a unified way.

The use of analytical fragility curves was proposed by Mastroberti et al. (2018) for the assessment of the economic feasibility of various combined seismic and energy retrofitting interventions. Seismic upgrading was assumed with the addition of RC walls or with TRM overlays on the masonry infills. Energy retrofitting on the other hand was assumed to be achieved with expanded polystyrene (EPS), polyurethane (PUR), aerogels and thermal windows. Of the possible combinations, TRM with EPS was found to be the most cost-effective retrofitting solution, as it allows for the simultaneous application of the insulation panels, both in terms of scaffoldings and surface preparation.

The economic feasibility of TRM + polystyrene insulation was also evaluated by Bournas (2018) and Gkournelos et al. (2019) using a simplified EAL-based procedure. The integrated retrofitting system was found to be more cost-effective in the long run compared to an energy upgrade solution alone, especially for structures with higher seismic risk, due to either their location or their inherent deficiencies. On those grounds, it is suggested that such retrofitting strategies should be considered for state subsidies.

Pohoryles et al. (2020) studied that same retrofitting scheme as a means to achieve the 2030 EU decarbonisation target of 30% less CO_2 emissions. Five different building typologies were considered (2 masonry and 3 RC) to cover practically the whole building stock in twenty European cities located in areas of different seismic hazard (five seismic zones) and climatic conditions (four climatic areas). In line with the previous work, the integrated approach was found to have shorter payback times in cases of medium to high seismicity than a simple energy retrofit. Moreover, it was estimated that to achieve the 2030 decarbonisation goal, the current renovation rate of 1% has to at least triple (≥3%).

5.5 Financial and technical barriers to combined retrofit interventions

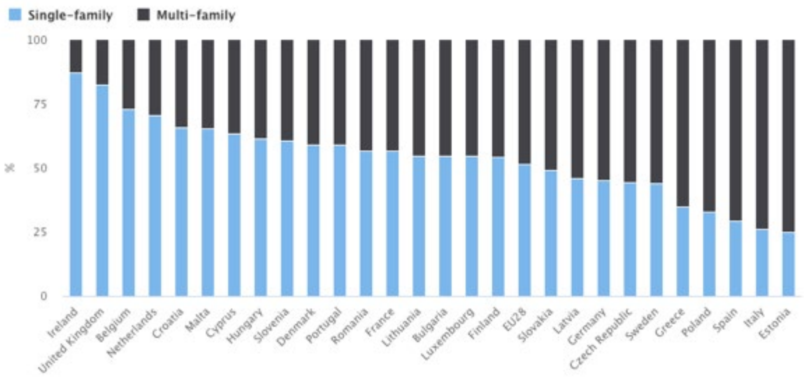
5.5.1 Financial barriers to building renovation

While the use of combined frameworks for the economical evaluation of seismic and energy retrofitting interventions has demonstrated their cost-effectiveness for areas associated with seismic risk, there are several financial barriers to overcome the high direct and indirect costs of said interventions. As described earlier, return on investment regarding energy efficiency measures is much more straightforward than in the case of seismic retrofitting. This clearly also relates to the cost-benefit calculations of combined interventions, in which reduced pay-back periods are associated with the probabilistic nature of seismic risk, and hence not necessarily giving a building owner a tangible return of their investments.

The high initial costs of building retrofit investments are an overwhelming barrier for many owners, even for measures that are cost-effective in the long term. In addition to the direct cost of the renovation and the related difficulty to sustain it, also other indirect or technical sources of costs should be taken into account. In particular, as shown in Section 5.2, most renovation options imply some level of disruption and need for relocation, which can generate significant costs and stress. Additionally, it often occurs that low-income households, i.e. the least able to invest in renovation measures, are also those living in dwellings with poor seismic and energy performance, which reduces the opportunity of undertaking renovation actions for the buildings with the highest seismic vulnerability and decarbonization potential (La Greca and Margani, 2018).

A further financial barrier to investments in building renovation is the so-called "split-incentive"/"landlord-tenant dilemma": in the case of rented properties, the expected savings might not be significant for the dwelling-owner because tenants would benefit from lower energy costs or increased living comfort and safety. "Split-incentive" issues are non-evenly distributed among EU countries, as the share of owner-occupancy in multi-family houses ranges from 23-26% for countries such as Austria, Germany, France, to over 65% in countries such as Italy, Spain, Romania, Bulgaria (Matschoss et al., 2013), where the "split-incentive barrier" may be less strong. In the case of multi-family dwellings, next to financial difficulties, a very significant obstacle is obtaining consensus on the retrofit expenditure, when both owner-occupants and rental tenants are living in the structure to be renovated (La Greca and Margani 2018). Muti-family houses however constitute a significant proportion (>60%) of dwellings in the EU's most seismic countries, such as Greece or Italy (**Figure 50**).

Figure 50. Share of single- and multi-family dwellings by country



Source: https://ec.europa.eu/energy/eu-buildings-factsheets_en

While the scientific evidence points towards clear benefits of integrated retrofitting in seismic areas at regional or societal scales, renovation needs to be incentivised through public funding to overcome these financial barriers. To promote building renovation, a system of fiscal incentives may however bring a solution, as presented next.

5.5.1 Incentives that favour integrated seismic/energy retrofits

To substantially favour the execution of integrated seismic and energy retrofit, information and engagement campaigns (at any level) are recommended to achieve a behavioural inclination towards more sustainable choices and decisional strategies. La Greca and Margani (2018) also include, as an alternative to public actions, contractors giving decision-support packages in their services, although these might not be perceived as impartial and clients could be unwilling to pay for this extra assistance.

In some cases, where decisions are hindered by conflicting interests in multi-family buildings, a possible solution may consist in engaging external parties – such as municipal agencies, housing associations, structural and energy consultants – to support and speed up decision making. In these specific cases, a useful contribution to reach consensus is given by solutions that minimise the disruption to the occupants during the renovation works, for example operating mainly from the outside of the building (La Greca and Margani 2018). In the case of "split-incentive barrier", a possible countermeasure consists in revising contracts to permit landlords to raise the rent of the retrofitted property, with an increase commensurate with the reduced energy bill paid by tenants and the enhanced seismic performance, and in any case, landlords could benefit from tax incentives. Moreover, the money saved by tenants on energy costs will leave more money left over for rent, reducing defaulting circumstances, and in a competitive rental market, a seismic-safe, low-energy and thermally-comfortable building will have better chances to be well rented or sold. Consequently, the "split-incentive barrier" might be overcome simply through appropriate information campaigns (La Greca and Margani 2018).

La Greca and Margani (2018) observe that fiscal incentives, such as tax deduction, tax credits and VAT reduction, are the most effective measure, so far, to encourage private investment in seismic and energy efficiency retrofitting. In Italy, in particular, for the last 50 years, there has been a VAT reduction from 20-22% to 10% for all costs related to building renovations and works (MEF, 1972). In addition, since 1998, there has been a gradual introduction of tax credits, allowing subtracting 36–65% of refurbishment costs from the tax due, with deductions equally distributed over 5 or 10 years (Parlamento Italiano, 1997; 2006; 2015). At the end of 2016, for the period 2017-2021, the shares have been consistently increased to 70-80% and 75-85% for seismic upgrades of, respectively, single-family and industrial and commercial buildings and multi-family buildings, according to how many classes (one or two) of seismic risk can be reduced by doing the intervention (MIT, 2017a; MIT, 2017b). Correspondingly, 70-75% of refurbishment costs for energy upgrades can be deduced from the tax due, according to the reached energy performance, whereas previously these were fixed at 55-65% (Parlamento Italiano, 2006; 2016).

These tax credits are due on a maximum cost of the works of 96.000 € for each property (the seismic one) and 40.000 € for each property (the energy one in multi-family buildings, higher for single-family houses). Indeed, the shares of tax credits are connected to the above-mentioned maximum costs for each property, plus the common part, in multi-family buildings, and are higher in multi-family buildings as well. Hence, the works result to be very convenient in the case of apartment buildings, thus going towards not only a more effective reduction of seismic risk (considering the higher exposure of multi-family buildings) but also a more attractive measure, contributing to solving some of the organizational problems mentioned for multi-family dwellings.

Recently, other important measures have been launched. For instance, for multi-family buildings combining energy and seismic retrofit interventions has been made more convenient by extending the higher share of tax credits given for the seismic retrofit alone (75-85%) to combined energy and seismic intervention, calculated over a maximum cost of 136.000 € for each property plus the common part (Parlamento Italiano, 2017). More recently, in the framework of the decree to relaunch the economic system after the COVID-19 pandemic, an even more convenient tax credit share of 110% has been introduced (Presidente della Repubblica, 2020).

5.5.2 Technical challenges and research needs

Most of the masonry buildings have however previous plaster layer on the outside, which can be replaced by other measures for seismic/energy upgrading (e.g. TRM). Compatibility of the combined retrofit solutions still requires the suitability of the retrofit material with the weaker substrate e.g. arising between existing mortars and eventual grouts used for injections or additional mortar-bed repointing works. This is valid also for reinforced plasters applied on the masonry wall sides which must respect the nature of lime-based mortars used in most masonry constructions. Moreover, when it is not possible to install thermal insulation on the exterior side due to aesthetic constraints, installing them on the interior side should be carefully evaluated due to the smaller capacity of internal insulation systems in controlling the humidity with related discomfort (as discussed in Section 3.2.1.2). This latter is particularly true for stone masonry buildings which constitute a large part of historical city centres.

Overall, despite combined retrofitting being a relatively new field of investigation, quite a number of research studies have already been published. Still, there is a lot of work that still needs to be done, for such combined retrofitting schemes to become the norm in renovation applications. 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 theoretically or evaluated through numerical models.

Moreover, there is a need to research, test and develop more integrated retrofitting systems. These may be based for example on smart combinations of materials so that the dual goal of structural and energy upgrading can be achieved simultaneously. Further research on this topic, both in terms of technological development of the existing interventions and new systems, and in terms of creating a framework, also through shared case studies, for a more detailed assessment of the cost of implementation, energy-saving, seismic improvement, disruption time, environmental impact, life span, recycling possibility, indoor environmental quality, potential health risks, degree of compatibility, potential damage and reduction of efficiency, life-cycle assessment, etc.,

In any case, it is of utmost importance that in any proposed scheme, the actual application cost is kept within reasonable limits, otherwise, its implementation in real practice will be practically impossible. The use of very expensive, exotic materials which are decades away from penetrating the markets, although tempting, is mainly of academic rather than practical interest. 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 on tomorrow's economies.

6 Conclusions

With the recent launch of the Renovation Wave initiative within the EU Green Deal, building renovation has been given a key role within the policies associated with the reduction of CO_2 emissions in the European MS. Retrofitting energy-inefficient buildings is instrumental to reduce the impact the built environment has on the EU total energy household. At the same time, recent earthquakes have caused significant economic losses, mainly in the seismic regions of Southern Europe. As a consequence of the poor energy performance, as well as the vulnerability of older buildings to seismic hazards, a large proportion of the existing EU buildings require both structural and energy upgrading.

Natural or man-made risks, such as fire or earthquakes may result in loss of investments in energy retrofitting, which has recently been recognised by the new EPBD. Cases of heavy structural damage to energy-retrofitted buildings have already been witnessed, thus highlighting the need for a holistic approach to the renovation of the existing building stock. The integrated retrofitting of buildings is of high relevance to policy measures related to the energy renovation of buildings, circular economy principles within the construction sector, improving the resilience to natural disasters, as well as protecting our built heritage.

Researchers have hence increasingly started to address the topic of integrated seismic and energy retrofitting of buildings, from both a theoretical and an experimental point of view. The present report provided a review and analysis of integrated techniques for the seismic and energy upgrading of EU buildings. A brief overview of typical seismic and energy deficiencies of the EU building stock, as well typical interventions for their improvement were presented first before recent developments on combined and integrated techniques were reviewed.

Based on the gathered scientific literature on integrated seismic and energy retrofitting by different researchers, four different broad groups 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. The encountered solutions were then analysed and compared in terms of their costs, the level of invasiveness and business downtime related to the retrofitting implementation, as well as the environmental impact of the materials used.

In terms of **exoskeleton solutions**, fully integrated shell technologies were proposed, including shell-grid solutions, starting from simple BRB-braces combined with solar shading, to material-efficient diagonal steel grids (diagrids) integrated with various thermal panels (PV, shading or thermal insulation). Shell-systems based on insulated RC walls, as well as RC frames combined with thermal insulation panels or masonry infills, were also proposed. In the former, full integration was achieved using thermal insulation as concrete formwork. Alternatively, shear wall solutions were proposed, in which the energy efficiency retrofit can be supported by the external steel structure. This can include any type of energy intervention, including green facades, photovoltaics or shading devices, but can also be used to increase the existing living space. Such solutions are highly invasive, as they completely change the external appearance of a structure, require space around the structure and need an additional foundation system. The significant change of external appearance of structure, may however be desirable in the context of the New European Bauhaus, to provide an architectural upgrade to existing concrete buildings. Moreover, with interventions done entirely from the outside, there is a benefit of reduced occupant disruption. The cost and environmental impact of exoskeleton solutions are however typically higher, particularly in the case of steel-braced solutions.

Integrated interventions on the existing building envelope were also proposed for their application to masonry and RC buildings. Different ways of achieving combined retrofitting can be distinguished. Firstly, strengthening of the envelope through composite materials (in particular TRM) can be combined with thermal insulation, which can be applied within the same intervention. This technology can be considered the most mature of all presented integrated retrofit options, as several experimental validations of the seismic-plus-energy system have already been carried out. Retrofitting with TRM has already been proven very effective in improving both in and out-of-plane capacity of URM walls and masonry infills. New developments in thermal mortars and cement-free mortars integrated with glass-fibre grids have also been presented, as they may have the potential of future applications of composite materials for structural and thermal upgrading. To date, however, additional thermal insulation is required to achieve combined retrofitting with TRM. TRM-based integrated retrofitting brings the advantage of external application and low disruptiveness, together with very high cost-effectiveness and low environmental impact.

Secondly, **prefabricated panels** can also be used to intervene on the existing envelope of a building. Solutions presented in the literature include TRM/TRC-based panels, integrated with thermal insulation, PCM or capillary tubes, as well as timber-based CLT or OSB panels with thermal insulation. The advantage of prefabricated panels over the wet layup of TRM retrofitting is reduced construction time, increased modularity and the potential for full integration of the structural and energy elements. Thirdly, the openings of existing URM walls can be strengthened by the provision of new windows with structural frames, which stiffens the structure while also providing improved thermal performance of the windows by the use of double- or triple-glazing or other modern fenestration options.

Rather than strengthening and improving the thermal capacity of an existing wall, the possibility of **replacing** at least one layer of the external building skin of masonry-infilled RC buildings was also explored. The existing infills can be (1) replaced by stronger and more thermally insulating bricks; or (2) replaced by infill walls that are deformable or decoupled from the RC frame. In the latter solution, a reduction in infill-frame interaction aims to control damage in the panels and the frames during earthquakes. In either case, additional thermal insulation is typically required, however sustainable bricks or bricks with thermal insulation may be used to reduce the environmental impact of the intervention. While replacing the external envelope is extremely invasive and disruptive, the costs associated with the intervention are typically low.

Finally, **interventions on horizontal elements** (roof and floors) were also mentioned. While only limited proposals have been made for integrated interventions on the horizontal diaphragms of existing structures, both seismic and energy interventions could have a high potential for integration. The example of the so-called Nested Building, which consists of constructing an entirely new inner shell for improving the seismic performance and energy efficiency of (historic) masonry buildings was given. There it was suggested to replace existing floors with CLT boards and to apply CLT panels and thermal insulation at the roof level.

Consideration was also given to **cultural heritage buildings**. Several researchers evaluated case studies of historic masonry structures, proposing theoretical approaches to their combined retrofitting. The main aspect for CHBs is that their external appearance can typically not be changed and for the preservation of the heritage value, only low-invasiveness interventions are often possible. Moreover, the historic substrate (e.g. stone masonry) of CHB buildings also means particular attention needs to be given to the type of materials used and their compatibility.

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. Despite reduced payback times, given the initial costs of interventions, financial barriers still exist for the implementation of combined retrofitting, which may only be overcome through some degree of public financing. Financial assistance could either take the form of subsidies or tax reductions, such as the *Eco-Sisma Bonus* system, recently applied in Italy. In any case, simple energy upgrading on structurally unsafe buildings should not be promoted. In other words, the structural integrity must already be guaranteed, if energy upgrading alone is to be financed.

Finally, from a technical point of view, the readiness of integrated retrofitting solutions is still questionable in many cases. To date, only a few of the technologies presented are already conceived to be fully integrated or coupled. Most often the combined seismic and energy purpose of those interventions has emerged only very recently, and there is still a lack of comprehensive experimental and analytical works that tackle the two aspects together, in an integrated evaluation. While the field of combined structural and energy retrofitting is undoubtedly still in its infancy, valuable results and insights have already been shared among the scientific community. Experimental research has to advance further, towards the direction of fully integrated retrofitting systems, which can be applied simultaneously at a low cost. That, combined with some 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.

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Annex: Calculation of environmental impact

The calculation of the environmental impact presented in Section 5.3 is performed for the same reference building as the cost calculation in Section 5.1, i.e. assuming a 3-storey building with 200 m^2 (10mx20m) of floor surface, 3 m of inter-storey height. The building is characterized by a total floor area of 600 m^2 (plus the roof) and a surface of the external walls of 540 m^2. It is assumed that the combined interventions are applied to all of the external walls and for all the floor levels (except for the ground floor but including 200 m^2 of the roof).

The embodied carbon (cradle-to-gate) of the materials **only**[14] are taken from the latest version of the ICE database (V3.0 – 10 Nov 2019)[15], as shown in **Table 8**. The embodied carbon in $kgCO_{2e}$ per kg of material from is presented, as well as the density of the material used for calculating the embodied carbon per volume of the materials.

Table 8. Properties of materials and systems for embodied carbon calculation

Material	Embodied Carbon [$kgCO_{2e}/kg$]	Density [kg/m^3]	Embodied Carbon [$kgCO_{2e}/m^3$]
Hollow clay brick	0.21	2,000	426.00
AAC brick	0.28	600	168.00
Steel section	1.55	7,800	12,090.00
Mortar (1:3 cement:sand mix)	0.20	1,650	330.00
Glass fibre	8.10	2,680	21,708.00
Reinforced concrete (C25/30)	0.10	2,400	247.20
CLT	0.44	485	211.95
Timber OSB	0.45	650	295.75
Aluminium (louvers)	6.67	2,700	18,009.00
Wood fibre insulation	0.98	360	352.80
Rock wool	1.12	100	112.00
EPS	3.29	35	115.15
PV module			67.00 (per m^2)
Window (15 mm triple glazed)			65.50 (per window)

Source: ICE database (V3.0 – 10 Nov 2019).

These values are then used in the calculation of embodied carbon per m^2 of floor area based on the quantities (e.g. thickness of panels, sizes of sections) suggested in the individual publications reviewed in Section 4. Note that for the strengthening and replacement solutions, the assumption of a window replacement (as proposed for these interventions) is also taken into account, assuming the use of triple-glazed windows (0.9x1.2m) in each one out of two frames. For the steel exoskeleton, a combination of photovoltaics, green walls and louvers is assumed to cover the envelope in equal quantities. The calculation is summarised for each of the interventions in **Table 9**.

[14] Embodied carbon of transport, construction works etc is hence **not** taken into account

[15] ICE (Inventory of Carbon & Energy) database (https://circularecology.com/embodied-carbon-footprint-database.html)

Table 9. Calculation of embodied carbon for the different integrated retrofit interventions.

		Thickness	Volume	Embodied Carbon	
		[m]	[m^3]	[$kgCO_{2e}$]	Per m^2 floor
Insulated RC wall (Pertile et al., 2021)	RC	0.06	0.9	222.5	13.3
	EPS insulation	0.14	2.1	241.8	14.5
	TOTAL				**27.9**
TRM + EPS insulation + window (Triantafillou et al., 2017)	Mortar (2mm per layer)	0.006	0.09	29.7	1.8
	glass fibre textile (3 layers)	0.000164	0.0025	53.5	3.2
	EPS	0.08	1.2	138.2	8.3
	New window (1 per 2 frames)				32.8
	TOTAL				**46.0**
Hollow clay bricks + EPS + window (Masi et al. 2017)	Hollow Bricks	0.2	3	1278.0	76.7
	mortar (ca. 80:20 ratio)	0.05	0.75	247.5	14.9
	EPS	0.08	1.2	138.2	8.3
	New window (1 per 2 frames)				32.8
	TOTAL				**132.6**
AAC bricks + EPS + window (Artino et al. 2018)	AAC Bricks	0.2	3	504.0	30.2
	mortar (ca. 80:20 ratio)	0.05	0.75	247.5	14.9
	EPS	0.04	0.6	69.1	4.1
	New window (1 per 2 frames)				32.8
	TOTAL				82.0
CLT + wood fibre insulation + window (Margani et al. 2020)	CLT panel	0.1	1.5	317.9	19.1
	mortar applied (30 mm)	0.03	0.45	148.5	8.9
	wood fibre insulation	0.065	0.975	344.0	20.6
	New window (1 per 2 frames)				32.8
	TOTAL				**81.4**
Steel exoskeleton (Ferrante et al. 2018)	HEA 240 steel section (1)	16 m	1024 kg	1587.2	95.2
	PV module (1/3 of frames)		5 m^2	335.0	20.1
	Aluminium louvers (1/3 of frames)	0.0018	0.01	162.1	9.7

	Green façade (1/3 of frames)			0.0	0.0
	TOTAL				**125.1**
RC frame exoskeleton + EPS insulation (Pozza et al., 2021)	3 RC columns (250mm x 250mm)	0.063m^2 (section)	0.56	139.1	8.3
	RC cross-beam (300mm x 400mm)	0.12m^2 (section)	0.6	148.3	8.9
	EPS 325 mm thick	0.325	3.71	427.5	25.6
	TOTAL				**42.9**

(1) For HEA 240 steel section the length and weight are provided, assuming a weight of 64 kg/m length.

List of abbreviations and definitions

AAC	Autoclaved Aerated Concrete
BEM	Building Energy Modelling
BIPV	Building Integrated Photovoltaics
BRAD	Buckling-restrained axial dampers
BRB	Buckling-restrained brace
CHB	Cultural Heritage Building
CLT	Cross-laminated Timber
DS	Damage State
EAL	Expected Annual Losses
ECC	Engineered Cementitious Composites
EPBD	Energy Performance of Buildings Directive
EPS	Expanded Polystyrene
EU	European Union
EIFS	Exterior Insulation Finishing System
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FRCM	Fibre-Reinforced Cementitious Mortars
FRGM	Fibre-Reinforced Geopolymer Matrix
FRP	Fibre Reinforced Polymer
FU	Functional Unit
GFRP	Glass Fiber Reinforced Polymer
GPM	Geopolymer matrix
HVAC	Heating, ventilation, and air conditioning
ICE	Inventory of Carbon & Energy database
ICF	Insulated Concrete Formwork
ISD	Inter-storey drift
ISO	International Organization for Standardization
ISTAT	Italian National Statistics Institute
JRC	Joint Research Center
LCA	Life-Cycle Assessment
LCT	Life Cycle Thinking
LSLS	Life safety limit state
MS	Member State
NHL	Natural Hydraulic Lime
OSB	Oriented Strand Board
PCM	Phase Change Material
PEC	Primary energy consumption
PUR	Polyurethane

PGA	Peak Ground Acceleration
PGAc	Peak ground acceleration (capacity)
PGAd	Peak ground acceleration (design value)
PUR	Polyurethane
PV	Photovoltaics
RC	Reinforced Concrete
RES	Renewable Energy Source
RM	Reinforced Masonry
SLV	Life safety limit state (Italian building code)
SSD	Sustainable Structural Design
TCP	Textile and Capillary tube Composite Panel
TRM	Textile Reinforced Mortar
UCPM	Union Civil Protection Mechanism
URM	Unreinforced Masonry
U-value	Thermal transmittance in W/(m^2K)
VAT	Value Added Tax
XPS	Extruded Polystyrene
ζ_E	Seismic risk index = PGAc/PGAd

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