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Integrated seismic and energy retrofitting of existing buildings: A state-of-the-art review

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ABSTRACT

Ageing of the building stock is an issue affecting many regions in the world. This means a large proportion of existing buildings being considered energy inefficient, with associated high energy use for heating and cooling. Through renovation, it is possible to improve their energy-efficiency, hence reducing their significant impact on the total energy household and associated greenhouse gas emissions. In seismic regions, additionally, recent earthquakes have caused significant economic losses, largely due to the vulnerability of older buildings not designed to modern standards. Addressing seismic and energy performance by separate interventions is the common approach currently taken, however to achieve better cost-effectiveness, safety and efficiency, a novel holistic approach to building renovation is an emerging topic in the scientific literature. Proposed solutions range 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. To identify pathways to combined seismic and energy retrofitting of buildings, a state-of-the-art review of all materials and solutions investigated to date is presented. This is followed by a critical analysis of their effectiveness, invasiveness, building use disruption as well as their impact on the environment. The assessment of current combined retrofitting research highlights a great potential for their application, with a potential to provide cost-effective renovation solutions for regions with moderate to high seismic risk. Still, to-date there is a lack of experimental research in this field, a need for further work on truly integrated technologies and their validation through applications on existing large-scale buildings. Moreover, there is a need for adequate design methods, regulations and incentives that further the implementation of integrated retrofitting approaches.

1. Introduction

The climate emergency means we need to find immediate solutions to reduce the greenhouse gas emissions. The building sector has to play a significant role in this reduction, given it is responsible for 35% of the total consumption of energy and 38% of greenhouse gas emissions globally [1]. To achieve reductions in energy consumption, improving the energy efficiency of buildings through renovation

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is needed. In the EU, this for instance emphasised in the European Green Deal (Communication 2019/640) and the associated *Renovation Wave* strategy [2]. Similar initiatives for improving the sustainability of and decarbonising the building stock can be found, e.g. in the U.K [3] or the U.S.A [4] where recent polices addressing the renovation of buildings have been implemented. Similarly, in developing countries with significant and rapid improvement of living standard, e.g. India and China, policies for improving energy efficiency standards are being implemented. In China (where the total building floor area doubled between 2000 and 2015 [5]), the Technical standard for nearly zero energy buildings was implemented in 2019 [6], while in India, the Bureau of Energy Efficiency (BEE) has developed a labelling scale for residential buildings to provide information to consumers about the energy efficiency program standard of the homes to be built across the country [6]. The latter is estimated to lead to energy savings up to 40%.

The ageing of the existing building stock also means that a considerable percentage of it has been constructed to outdated building codes and seismic standards [7]. This poses a great societal risk, as highlighted by the vulnerability of the existing building stock to recent earthquakes, leading to structural damage, significant economic losses, but also to severe injuries and loss of human lives [8–12]. As more buildings approach the end of their conceived-for service life, other risks related to durability of materials also emerge, including excessive corrosion of steel reinforcement or structural steel members which can greatly decrease the capacity of structural elements and even result in their collapse [13,14]. Structural retrofitting may hence not be only required in earthquake-prone areas, but to a larger proportion of EU buildings.

Given the scale of the problem, addressing energy-inefficiencies and structural deficiencies of existing buildings through their replacement is not a viable option, as it would have a severe impact on the existing urban fabric and society, and would not be financially feasible or environmentally sustainable. Instead, preference should be given to the lifetime-extension of existing buildings through maintenance, repair, and renovation. Given that there is a large proportion of buildings in need for upgrading [15], the scale of refurbishment works and required investments is however significant. Uptake of renovation is however still low, for instance annual renovation rates are ranging between 0.4 and 1.2% in EU countries [16].

To promote renovation and ensure the longevity of energy upgrading investments, a holistic approach to building renovation could be instrumental. Until recently, repair and renovation efforts and related policies were however mainly directed to the energy upgrading of buildings alone, without taking into account their structural integrity. Promoting such a holistic view on building renovation is crucial, as disregarding the structural integrity of a building may cause misleading expectations on actual savings for an energy-retrofitted building, as energy upgrading alone does not lead to any reduction in structural vulnerability. Investments in energy efficiency measures may be completely lost if a structure is damaged or collapses, e.g. in the event of an earthquake [17]. Similarly, seismic retrofitting interventions alone could compromise thermal comfort if a building's energy efficiency is not considered.

In the scientific literature, the topic of integrated seismic and energy retrofitting has gained traction over the last five years. New methodologies are required for combined assessments of existing buildings, as well as for evaluating the potential benefits from integrated interventions. Including energy efficiency and seismic resilience (e.g.: [18], as well as life-cycle costs (e.g.: [19]8) in the assessment of existing structures is critical for informing the decision-making process in building renovation. To address the technical feasibility of integrated retrofitting implementations, different materials and technologies have been proposed by various research groups and an overview of their developments is presented here. This paper presents the first state-of-the-art review on the emerging scientific research on materials and technologies for integrated seismic and energy retrofitting. An analysis and comparison of the presented technology options is then presented based on the involved costs, the 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 for the implementation of integrated retrofitting are discussed, followed by a brief overview of incentives and regulatory frameworks that may help to overcome said barriers.

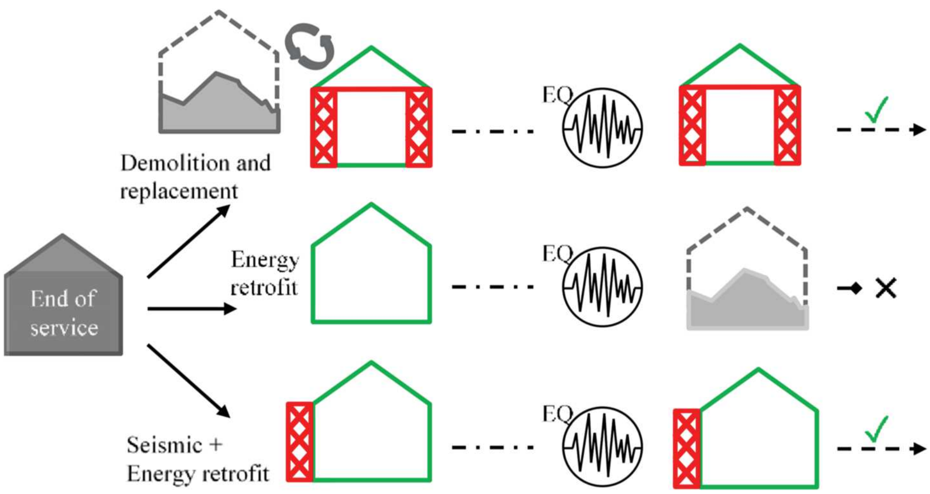


Fig. 1. End of service life of buildings: The effect of (1) Demolition and rebuilding; (2) Energy upgrading and (3) integrated energy and seismic upgrading in zones of seismic hazard (based on: [17].

2. Integrated retrofitting concepts and technologies

Structural and energy retrofitting of an existing building have so far generally been treated independently. A detailed description of such separate seismic or energy efficiency retrofitting solutions are not within the scope of this paper and the reader is referred to recent state-of-the-art reviews on these topics [20–25]. In regions with seismic hazard, the two needs of retrofitting (structural and energy) are however inherently linked, given that seismic damage or collapse would also affect the safety of the energy renovation investment. Fig. 1 compares demolition and replacement of an existing building with two different retrofitting approaches for an existing building. In the first one, only energy retrofitting is applied, which leaves it vulnerable to a potential seismic event. In the event of an earthquake within the structure’s lifespan, the occurrence of damage is likely, given that the structural deficiencies have not been addressed. Depending on the intensity of the event, the consequences may range from the need for minor repair works to the total replacement of the building. Obviously, in such a case, along with the building itself, the energy retrofit is affected and might be

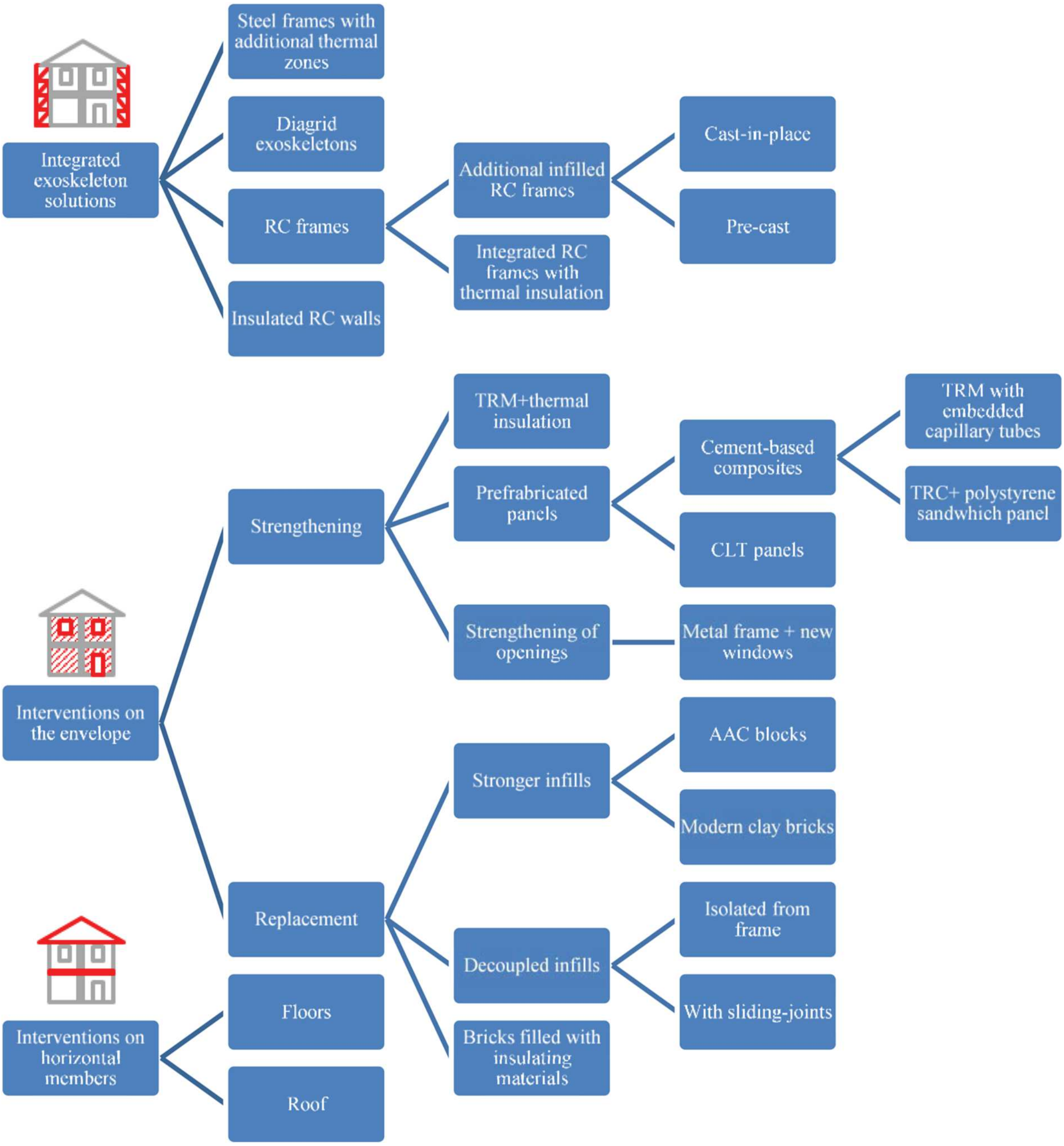


Fig. 2. Categorisation of combined retrofitting technologies.

lost as well.

On the other hand, if an integrated structural and energy upgrading scheme is applied, then the building's structural integrity can be regarded as safe with regards to the designed-for level of seismic intensity. 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 if the building can be considered structurally safe, according to modern standards. Otherwise, the risk of losing the energy investment is not justifiable as recent experience has shown [17].

The need for combined energy and structural retrofitting is nowadays acknowledged and has been reported by researchers in the field [17,18,26,27]. The application of an integrated retrofitting solution could be as simple as combining two independent techniques of structural and energy upgrading. In the case of simply combining two separate interventions, the total cost of the intervention would however be approximately equal to the sum of the two independent interventions, making such solutions less economically viable then techniques that can achieve both goals at the same time in an integrated fashion and hence at a lower cost.

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 retrofitting intervention 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. Recently, a framework for combining seismic and energy retrofitting interventions was proposed by Menna et al. [28]. In this framework, attention is placed on ensuring compatibility between seismic and energy retrofitting techniques according to their respective performance target, their level of disruption and intrusiveness, and time and cost of the respective intervention. The proposed framework hence aims to ensure that seismic and energy upgrading interventions with similar disruptiveness, cost and construction time are combined to achieve specific seismic and energy performance targets. The latter are defined in terms of an improvement in safety index ($\zeta_E = PGA_C/PGA_D$) at the life safety limit state (SLV) according to the Italian Building code [29], and in terms of the reduction in primary energy consumption (PEC) achieved by the intervention, respectively.

Integrated techniques aim to achieve energy and seismic performance improvement at once, with a single system or material, guaranteeing the required performance levels both in terms of seismic safety and energy efficiency. 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 broadly grouped into:

- Exoskeleton interventions;
- Improvement of envelope elements to achieve higher energy and seismic performance;
- Replacement of envelope elements by higher performance elements;

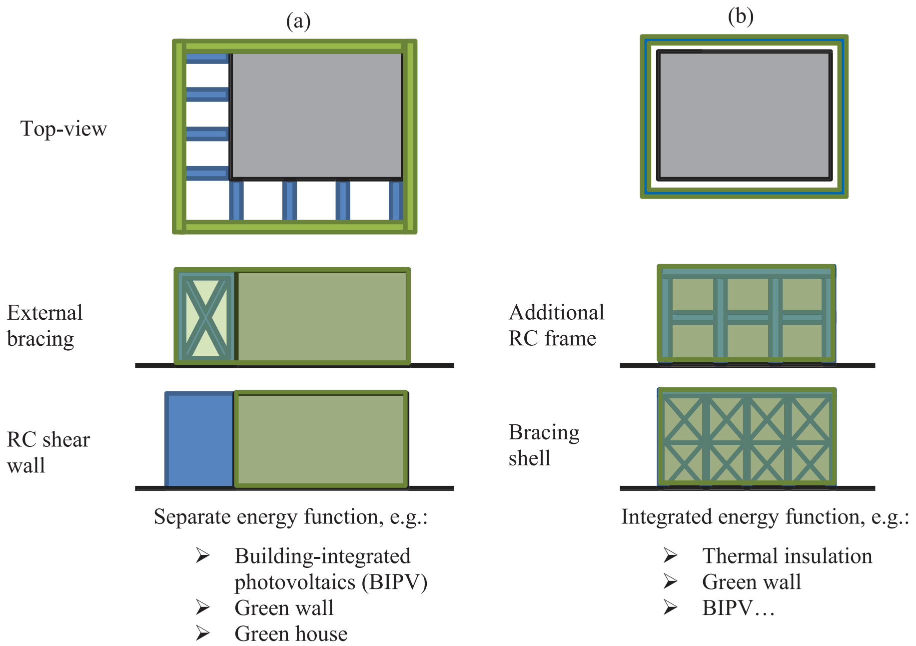


Fig. 3. (a) Wall and (b) shell layouts for structural exoskeletons.

- Combined interventions on horizontal elements, i.e. roof and floors.

Fig. 2 aims to provide an overview and categorisation of the identified combined retrofitting technologies.

While not all the interventions presented here-in 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. Completely separate interventions, e.g. base isolation combined with energy upgrading of a building, are however out of the scope of this review.

2.1. 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 [30]. Since the 1980s the use of external auxiliary structures is considered one of the possible options for providing additional strength and stiffness to existing RC buildings with low dissipative capacity. It is possible to divide structural exoskeletons into two main categories: (i) wall-like systems (introducing shear walls or braced frames Fig. 3a) and (ii) shell-like systems, as in Fig. 3b, exploiting a box-structural behaviour [26]. For a recent state-of-the-art report on the use of structural exoskeletons, the reader is referred to Di Lorenzo et al. [31].

The application of exoskeletons for building renovation 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 [26]. 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. Still, exoskeleton solutions are not always applicable due to the need of space around the structure and need for an additional foundation system (e.g. not feasible in densely built-up areas) and significant change of external appearance of structure, which may not be desirable or allowed in some cases. Additionally, as forces are usually transferred from the existing building to the exoskeleton by means of connections at the floor level, if the horizontal diaphragm is not stiff and resistant enough, the intervention might not be effective.

As shown in Fig. 3, 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 (Fig. 3a); 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 (Fig. 3b).

The first combined retrofitting application appears to be the renovation of the Midorigaoka-1st building of the Tokyo Institute of Technology completed in 9 months without the need for tenant-relocation [32–34]. It made use of a shell exoskeleton (Fig. 3b) combining Buckling Restrained Braces (BRB) for additional seismic energy dissipation capacity, and louvers for improved shading, hence reducing solar heat gains. An experimental study on representative RC frames showed the retrofit could prevent brittle shear failure and 2% inter-storey drift (ISD) was reached without any damage to the frame [34], while a simulation study showed reductions in solar radiation up to 66% through the louvers, with a reduction in annual energy consumption of up to 8% [35].

The use of steel-braced shear wall exoskeleton systems proposed by Marini et al. [26] (Fig. 4a) provided seismic strengthening while supporting separate energy efficiency systems (Fig. 4b). 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 1970s case study RC building through numerical analyses which showed significant improvements in seismic behaviour with a displacement capacity exceeding the demand at the life safety limit state (SLV) of the Italian Building Code [29], while stationary thermal analyses demonstrated a 70% reduction in heating energy consumption.

A similar system, using steel or timber frames was proposed [37], where additionally to thermal insulation, the external structure also provides thermal buffer zones, helping to reduce solar radiation in summer, providing solar heating in winter, and supporting plug-and-play installations for new HVAC systems, as well as generating additional living space in the form of balconies or extra rooms, depending on the user's needs. While the proposed retrofitting scheme was assessed to have a higher upfront cost compared to a deep energy renovation (+16.5%), the system can result in significant savings when considering the reduced need for resident relocation and the increase in real-estate value due to the increased living space and enhanced architectural value and user comfort. For a case study in Greece, based on seismic response spectrum analyses, an exoskeleton with braced steel frames (with HEB 240 sections) acting

Fig. 4. (a) Shear-wall structure; (b) energy retrofitting supported by the exoskeleton: adjustable louvers, solar greenhouses and filter spaces [36] - CC BY 4.0).

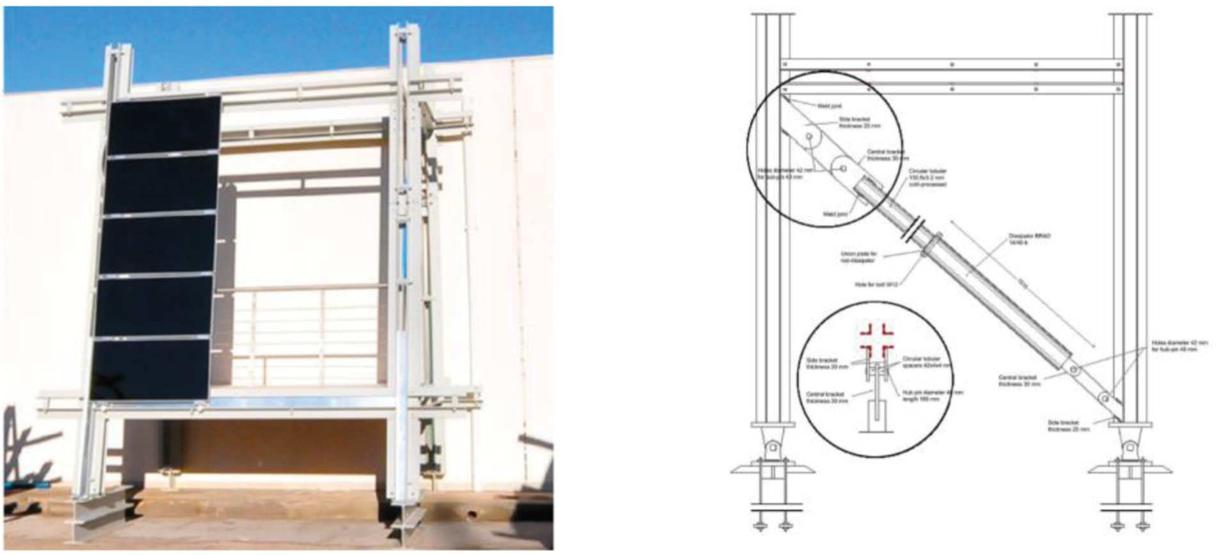
as shear walls can achieve reductions in displacement demand (between 16 and 26%) at the design earthquake. Additionally, a reduction in energy consumption up to 75% in the winter months and overall reductions of 35% were reported based on simulations for three case study locations (Greece, Italy and Romania).

More recently Foti et al. [38] built a prototype dissipative frame element, shown in Fig. 5a, to be used as a modular "kit" that allows to seismically retrofit a building, to make it energy self-sufficient and, possibly, also produce energy (through photovoltaics). Similarly to the solutions described previously, the elements could also be used to host thermal buffer spaces, shading systems or rainwater collection modules. Within the external steel frame, buckling-restrained axial dampers (BRAD) can be installed for additional seismic protection of the building, as shown in Fig. 5b, which can act as replaceable "seismic fuses" concentrating plasticity and damage during an earthquake. For a case study 1980s residential building in Southern Italy, the seismic behaviour, evaluated through FEM, was shown to be improved with reductions in roof-drifts of 41.3% and 36.8% in the building's weaker and stronger directions, respectively. In terms of energy efficiency, significant reductions in energy consumption can be achieved, while, if installed, the PV panels can generate up to 100% of the energy consumption of the heat pump for heating and cooling.

An alternative integrated exoskeleton system can be achieved by using diagonal grids ("diagrids") as exoskeletons, which contain directly façade elements for structural, energy and architectural improvements, as studied by Labò et al. [39–41] and D'Urso and Cicero [42]. From the structural point of view, the diagonal members are designed to intersect at the 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. Following the principles of Life Cycle Thinking (LCT), the diagrid can be fabricated from recyclable/reusable materials, and repairable, adaptable and fully demountable elements. 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 Ref. [40]. D'Urso and Cicero [42] implemented a parametric optimisation algorithm to find the most material efficient diagrid exoskeleton and different design ideas for integrated retrofitting were then elaborated, as shown in Fig. 6, including renewable energy production (e.g. BIPVs), vertical gardens or "green walls" that contribute to passive cooling, and solar shading devices, e.g. louver systems, that provide control over solar radiation and natural lighting. In either case, the energy savings (or potential energy production, e.g. through solar panels), depend on the specific options chosen for the energy efficiency modules attached to the exoskeleton, hence in any case, both costs and energy savings can be assumed to vary largely.

The concurrent seismic and energy upgrading can be also achieved by using RC frame exoskeletons [43], as in Fig. 7a, or by using precast auxiliary RC frames [44,45], as in Fig. 7b. The external RC members can be designed according to the local seismicity, while additional masonry infill walls ensure improved thermal insulation of the building. However, this intervention can be complemented with other energy efficiency solutions to make it suitable 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 (covering the largest part of Italy). 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.

Similarly, a shell exoskeleton system using tightly-spaced, cast-in-place external RC frames, as shown in Fig. 8, and prefabricated EPS modules, which provide the formwork of the RC frame, as well as increasing energy efficiency, was recently proposed and is currently tested in the TIMESAFE project [46]. In an initial FEM pushover evaluation of a retrofitted frame, the yield force was



(a) (b)

Fig. 5. (a) Prototype of an element of the dissipative frame exoskeleton with integrated photovoltaics (PV), (b) dissipative BRAD in the perpendicular frames [38] - CC BY 4.0).

Fig. 6. Different design options for a holistic upgrading of RC building with a diagrid exoskeleton [42] - CC BY 4.0).

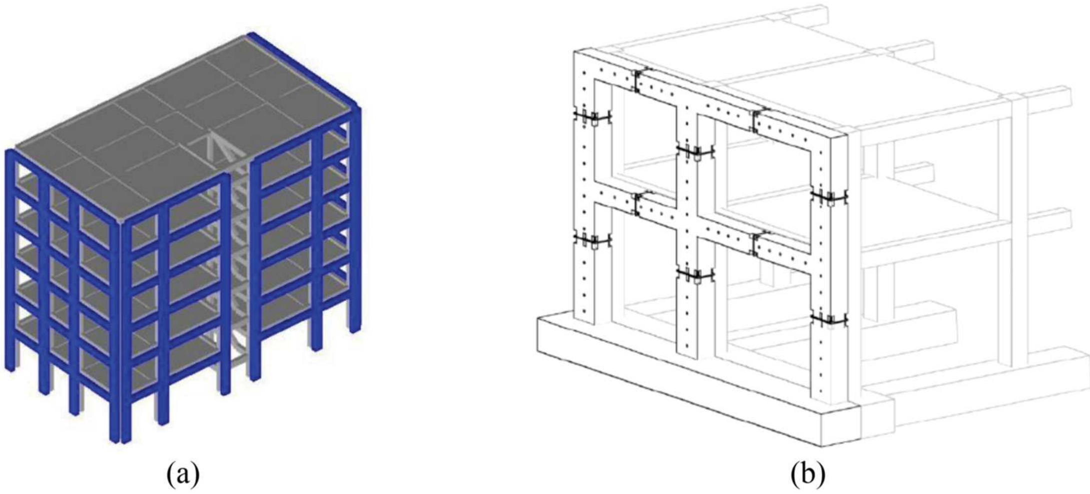


Fig. 7. (a) 3D view of a case-study structure with RC frame exoskeleton [43] - *CC BY 4.0);* (b) alternative using precast frame elements [44] - *CC BY 4.0).*

doubled, while the displacement capacity increased by nearly 300%. At the same time, the U-value for a typical infill wall was shown to be potentially reduced from 1.86 to 0.15W/(m^2K), as well as showing improvements in sound insulation through acoustic analyses.

Finally, constructing a new structural system with external foundations integrated with a thermal coating has been proposed by Pertile et al. [47–49]. The shell-exoskeleton system consists of a thin structural RC wall cast in-situ between pre-assembled layers of insulating material, functioning as permanent formwork (Insulated Concrete Formwork, ICF) and providing thermal insulation to the building envelope, as shown in Fig. 9. Note that the use of concrete makes this system not reversible or reusable, and potentially less environmentally friendly. The wall's reinforcement is designed depending on the building's characteristics and is connected with the existing structure at the beams of the structural frame (Fig. 9a) and at foundation level (Fig. 9b). The thermal transmittance in the case of using two polystyrene layers with 150 mm total thickness, is equal to U = 0.21 W/m^2K, which is under the limit foreseen for climate zone F, corresponding to the coldest climate in Italy. Quasi-static cyclic tests on two RC frames and two masonry wall specimens upgraded with ICF demonstrated a good connection of the system to the specimens, but occurrence of brittle failure making it a *non-dissipative* system in the design calculations for seismic strengthening [48]. Finally, a numerical evaluation of the retrofit applied to different case study (masonry and RC) buildings demonstrated a reduction in displacement demand up to 85% at the SLV limit state [49].

2.2. Integrated interventions on existing building envelopes

Given the large vulnerability and high energy transmittance of vertical building envelope elements (e.g. infill walls or structural masonry), particular attention is paid to intervening on external walls, strengthening the existing elements while additionally providing thermal insulation. Typical thermal retrofits nowadays use mineral wool, polyurethane (PUR) or polystyrene (EPS or XPS) as insulation materials, which have thermal conductivity values (λ) around 35 mW/m·K [25], while very low values of 3.5–8 mW/m·K can be obtained for Vacuum insulation panels (VIPs), or advanced materials like aerogel-incorporated plasters with λ-values between 10 and 15 mW/m·K [50,51]. Different avenues can be identified in the literature such as the application of composite materials or prefabricated panels, either cement-based or timber-based. Another type of solution consists in local strengthening of the existing openings integrated with substitution of old fenestration, when the latter have to be replaced. In the case of all envelope strengthening

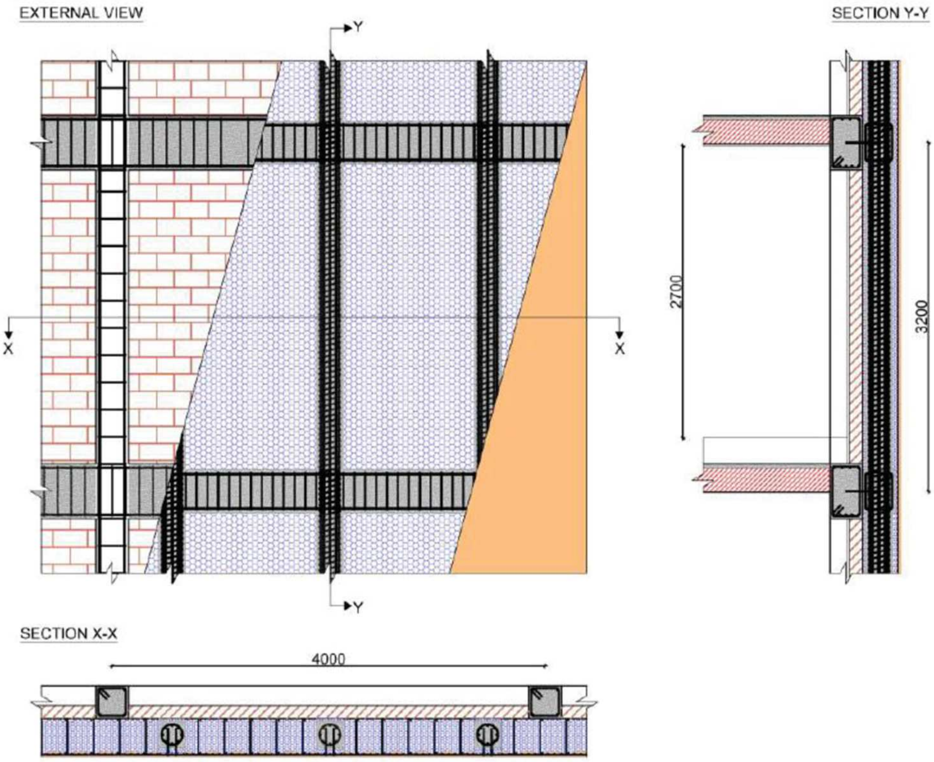


Fig. 8. RC-framed double skin solution [46] - CC BY 4.0).

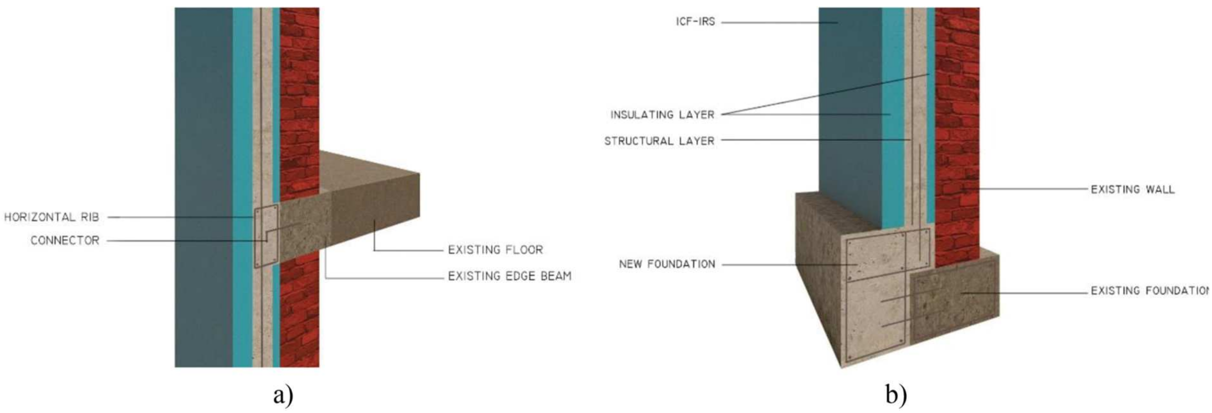


Fig. 9. Insulating concrete formworks: a) Connection of the system to storey beams and b) foundations based on (based on [48].

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.

2.2.1. 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. Several strengthening solutions using composite materials have been tested and a summary is provided in Ref. [52]. These range from textile-reinforced mortars (TRM), fibre-reinforced polymer sheets, which are bonded using epoxy resins (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.

The use of TRM in integrated seismic and energy retrofitting of building envelopes has been particularly investigated (e.g: [27, 53–56]. 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. Next to its relatively low cost, TRM has a high strength-to-weight ratio and high compatibility and bond with concrete and masonry substrates [57,58]. Additionally, compared to FRPs, TRM has better performance in terms of fire resistance [53,59] and behaviour at high temperatures (e.g.: [60–63].

As shown in Fig. 10, TRM can be easily applied together with different thermal insulation solutions. Bournas [27] 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.

In terms of experimental investigations, combined TRM and foamed polystyrene or foamed cement insulation were tested by Triantafillou et al. [53,54]. Various configurations of insulation and TRM-placements were investigated on masonry wallettes subject to out-of-plane loading and their fire behaviour was evaluated after their exposure to temperatures up to 870 °C [53]. It was found that the out-of-plane strength of masonry walls retrofitted with TRM and foamed polystyrene (+200–340%) was superior to that of TRM-strengthening alone (+170%), mainly due to the increased lever arm. In terms of out-of-plane deformation capacity, the combined system was again more effective than the TRM alone, with improvements by 140–145% [53,64]. The failure mode was textile rupture when the TRM was placed directly on the masonry surface, but debonding was observed when placed on top of the thermal insulation (e.g. Fig. 11). 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.

This retrofitting system was also found to be highly effective in improving the in-plane behaviour of masonry walls [54], testing two- or one-sided jacketing and placing the insulating panel either on the outer face or between the TRM and the masonry. The positioning of the TRM and the insulation material was found not to affect the in-plane response, as long as proper bond between the different layers was achieved. Moreover, single-sided application only led to a slight reduction in effectiveness, which is beneficial as it allows to perform all the work from the outside of the structure, drastically reducing the cost and the disruption of building occupancy.

Gkournelos et al. [55] tested the effect of in-plane damage on the out-of-plane behaviour of TRM-retrofitted masonry wallettes insulated with foamed polystyrene. Next to an improved in-plane behaviour, the out-of-plane capacity of the retrofitted specimens was significantly improved. Again, the out-of-plane behaviour of the combined seismic and energy retrofitted specimens presented a better behaviour than the TRM retrofit alone due to the increased lever arm. In the insulated specimens, debonding of the insulation was

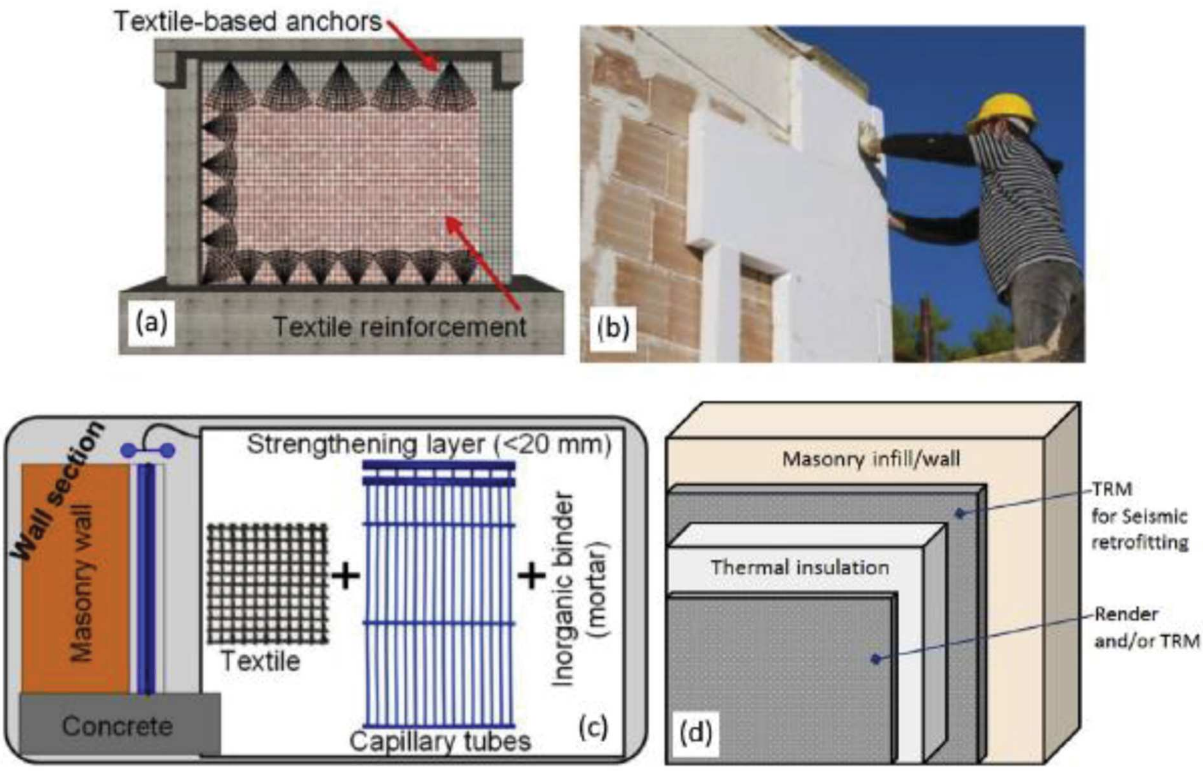


Fig. 10. Possible configurations of TRM and energy upgrading solution: a) Infills and RC structure retrofitting with TRM, b) Insulation of a building envelope, c) TRM + capillary heating tubes and d) TRM + thermal insulation material [27] - CC BY 4.0.

Fig. 11. Debonding at the insulation–masonry interface (a) one layer; (b) two layers of insulation [64] - CC BY 4.0).

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. This type of solution is also investigated on a RC full-scale building currently undergoing testing at the JRC's ELSA laboratory within the iRESIST + project [56].

In terms of energy performance improvements, case studies evaluated through building energy modelling (BEM) for different climatic conditions, have shown that large reductions in heating and cooling energy consumption can be achieved through applying thermal insulation together with TRM [52]. Savings in total energy demand varied with the original building's envelope material and climatic conditions of the case study location, with savings ranging between 37% for more recent construction (1970s and 80s) in warmer climates, up to 78% for older low-rise buildings placed in colder climatic regions.

Along the same lines, Giaretton et al. [65] 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. 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 combined retrofitting, 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.

Very recently, the use of Steel Fibre Reinforced Mortar (SFRM) combined with thermal insulation materials, as shown in Fig. 12, was also explored [66]. SFRM consists of steel fibres randomly dispersed in a thin layer of mortar and the proposed thermal insulation consists of either (1) a 50 mm thick panel made of needled fibreglass and silica aerogel, or (2) an 80–120 mm thick layer of wood fibres. These can be adjusted depending on the local energy upgrading requirements. With the retrofit, the U-value of the walls can be improved from 1.038 W/(m^{2}K) to 0.242–0.335 W/(m^{2}K) for the aerogel panel or wood fibres, respectively. Through a detailed BEM of a case study residential masonry building from the 1960s in L'Aquila, Italy, a reduction in energy needs by 17.1% was demonstrated for the latter, more cost-effective solution. Additional replacement of the windows would lead to savings up to 29.3%. The seismic improvements were verified using FEA, showing a displacement capacity five times larger than the demand at the SLV of the Italian NTC2018 guidelines [29].

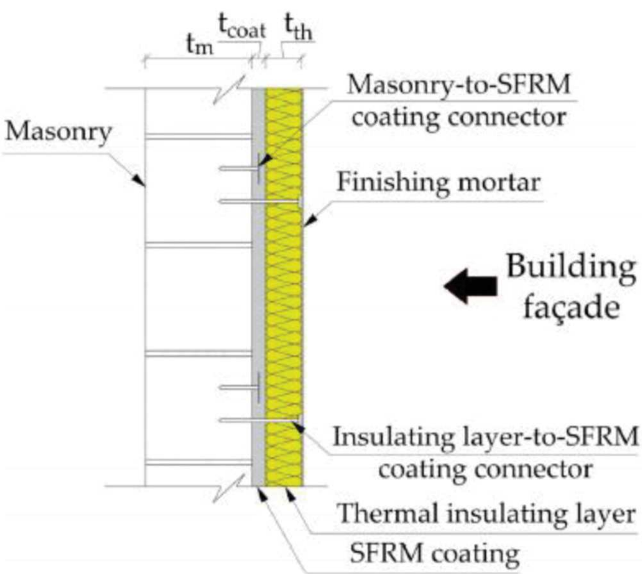


Fig. 12. Steel Fibre Reinforced Mortar (SFRM) combined with thermal insulation [66] - CC BY 4.0.

TRMs by themselves have a low insulating capacity, hence they need to couple with thermal insulation to achieve a combined seismic and energy retrofitting. Several studies have however investigated the modification of mortars to yield better thermal properties. Borri et al. [67] 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, achieving reduction in thermal transmittance (U-values) between 34 and 45%. Still the lowest achieved U-value (0.71 W/(m^2K)) would not be sufficient for the most stringent guidelines. In diagonal shear tests, 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%.

Coppola et al. [68] investigated the use of lightweight cement-free alkali-activated mortars, in which a GFRP mesh is embedded, which achieved a compressive strength of 8 MPa, compared to 2–2.5 MPa for a traditional mortar, as well as a thermal conductivity of 0.35 W/m·K, about 75% lower than the traditional mortar (1.30 W/m·K). While the results are promising, the performance of the FRP-grid strengthened mortar was not yet tested for structural strengthening. Longo et al. [69–71] have explored the use of lightweight geopolymer-based mortars (GPM) embedded with GFRP mesh (FRGM). 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 Natural Hydraulic Lime (NHL) mortar used for FRCM systems. Under diagonal compression, masonry panels strengthened with NHL-FRCM achieved a higher improvement (+129%) compared to the novel FRGM (+72%) [71]. FRGM achieved however a higher reduction in U-value, −46%, from 2.082 W/(m^2K) of an existing URM wall to 1.126, while the equivalent FRCM specimen had a U-value of 1.862.

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 a multi-layered approach with the addition of thermal insulation materials [27].

2.2.2. Prefabricated integrated panels

The use of prefabricated Textile-Reinforced Concrete (TRC) panels was also proposed for integrated retrofitting of existing building envelopes [72,73]. Specifically, capillary tube heating systems are embedded with a carbon textile in a layer of mortar to create a precast TCP panel (Textile and Capillary tube Composite Panel), as shown in Fig. 13. 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. Another recently proposed panel system for combined structural and energy retrofitting is that of Sousa et al. [74]; who developed multi-function sandwich panels comprising thin faces of recycled steel fibre reinforced micro-concrete and a polystyrene core (XPS or EPS).

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. Multiple studies have proposed the use of CLT and OSB panels as an integrated retrofitting strategy for either RC buildings [75–78] or load-bearing masonry buildings [79–81]. Stazi et al. [75] demonstrate 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 [75] 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) [82].

In the e-SAFE project [76,83,84], prefabricated CLT (Fig. 14a) are connected to masonry infills of RC buildings using seismic energy

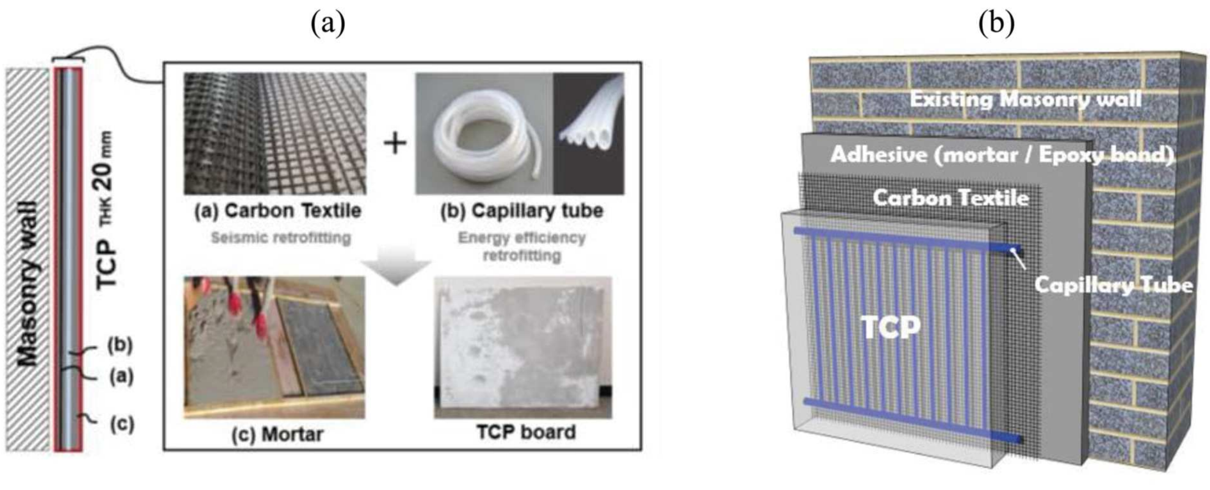


Fig. 13. TCP combined seismic and energy retrofitting panel, (a) composition; (b) application on a masonry wall [72] - CC BY-NC 3.0).

dissipation devices to reduce drift demands during earthquakes, which has been previously shown to improve the seismic behaviour, by reducing the energy transmitted from the CLT panel to the frame [85,86]. Experimental investigations on novel friction connectors for the integrated CLT panels have recently been carried out within the framework of the e-SAFE project [87], showing promising results at component-level. The effect of the system on the energy efficiency of an RC building was evaluated for a case study in Southern Italy. 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)). Numerical studies using BEM showed a decrease in overall annual energy demand for heating and cooling up to 56%. Further studies on two different timber-based integrated retrofitting panels applied to a pilot building in Southern Italy have recently been conducted [88], highlighting a reduction in energy needs for space heating and space cooling decrease by 66% and 25%.

Finally, a CLT-based retrofitting technique is presented by Valluzzi et al. [80]; in which the building is entirely refurbished from the inside as shown in Fig. 14b. 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 Fig. 14c). 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 panels combined with a rock-wool layer (8 cm) ensure a reduction of U-value for various masonry types: 49% for solid clay brick masonry, −69% for hollow brick masonry, −87% for stone masonry.

2.2.3. Strengthening of openings with structural window frames integrated with fenestration replacement

To retrofit masonry walls with openings (e.g. for windows or doors), introducing a steel frame for strengthening the opening 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 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 (e.g.: [89]. The use of a structural steel window frame has been recently tested for individual masonry wall specimens [90], which lead to significant increases in the deformation capacity (+25%), the peak strength (+40%), and cumulative dissipated energy (+147%). At the same time up to 60% of a building's energy losses can be associated with inadequate fenestration [91], savings in heating and cooling energy can hence be achieved by their replacement with new highly insulated windows (e.g. double-glazed windows with low-emissivity coatings, low-conductive frames, and inert gas), which can have up to six times lower thermal transmittance compared to older windows with U-values as high as 4.5 W/m^{2}K - 5.6 W/m^{2}K [92].

A combined retrofit of existing openings of masonry walls through new low-emissive and airtight fenestration surfaces with ductile steel frames has recently been considered (Caliò and Occhipinti, under review). For a numerical case study of a school building, costs and downtime periods for structural window frame retrofit were shown to be reduced compared to other retrofit solutions.

2.3. 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

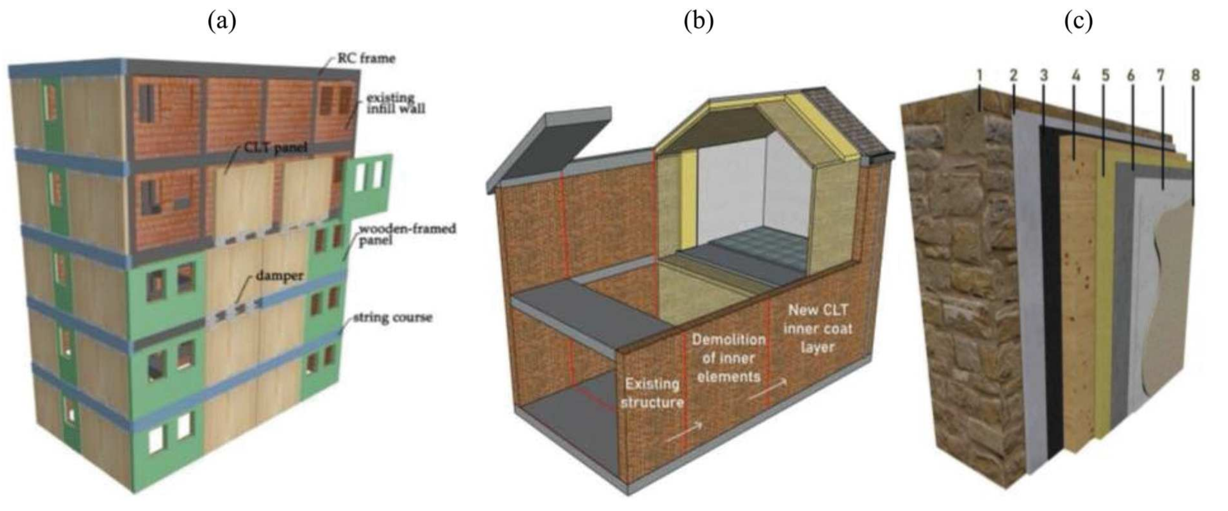


Fig. 14. (a) CLT panels used as external reinforcement in RC frames [76] - CC BY 4.0); (b) Nested Building retrofitting strategy; (c) Layers of retrofit with CLT timber and thermal insulation attached to the masonry wall [80] - CC BY 4.0).

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.

2.3.1. *Replacement with stronger and stiffer elements*

Masi et al. [93] 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 Fig. 15. This approach, developed in the framework of the latest Italian research 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 SLV limit state 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 [43].

A similar approach was taken by Artino et al. [94]; 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^2K)) compared to the initial one (U = 1.11 W/(m^2K)). 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 that this would not be sufficient in the case of a moderate or high seismic area. Through detailed BEM, it was calculated the total energy demand for heating and cooling was reduced by 38% and 27%, respectively.

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 Fig. 16. An experimental evaluation of such robust clay masonry infills by da Porto et al. [95] 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 2.2.2).

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.

2.3.2. *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 Fig. 17a and b, respectively. A more ductile behaviour with higher deformability, closer to a bare frame structure, can be achieved as shown in Fig. 17c. The use of special horizontal sliding joints (e.g.: [96], vertical sliding surfaces (e.g.: [97] or both horizontal and vertical special deformable joints (e.g.: [98] were proposed within the European FP7 project INSYSME [99].

Infill walls using horizontal sliding joints and modern clay brick units that can provide not only satisfactory structural properties but also adequate thermal and acoustic characteristics and durability were tested in-plane under cyclic loading, with damage significantly delayed (3.0% drift compared to 0.5%) and with a significantly increased deformation capacity compared to a traditional infill wall [96]. Vailati et al. [100] instead proposed a mortar-free infill system, to reduce the stiffness of the infill panels and enhance their deformation capacity, in which the brick units are connected through joints made from recycled plastic. The joints are designed to 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 [29] code could be safely sustained [101].

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 Fig. 17b. The use of

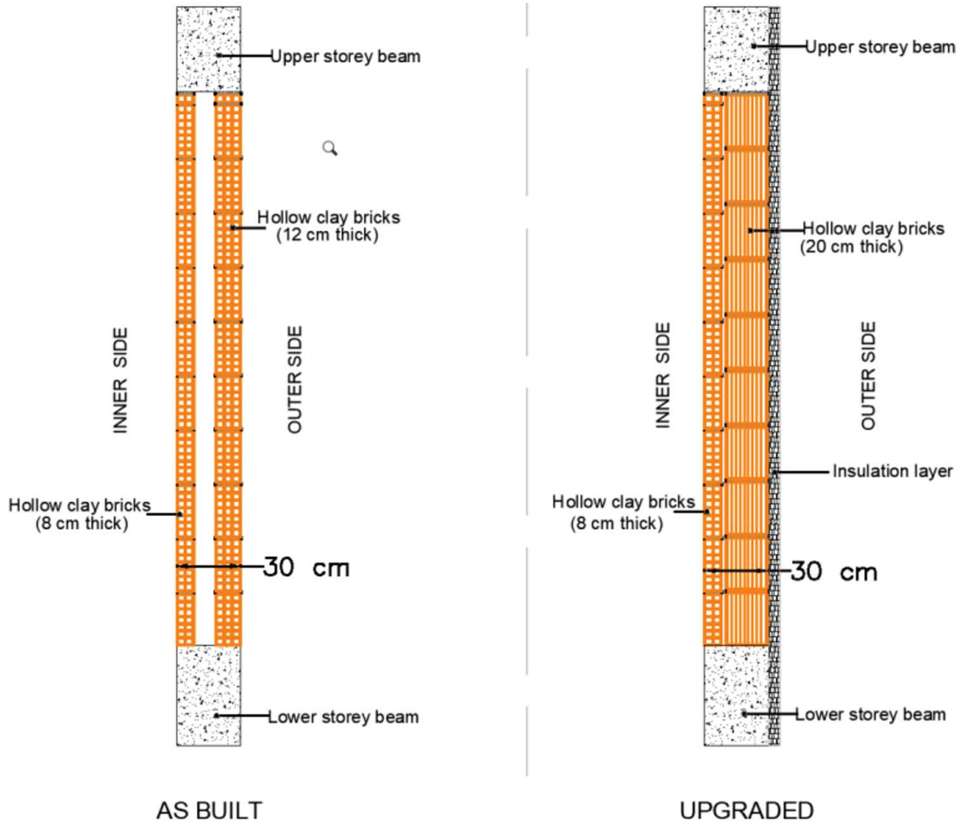


Fig. 15. Replacement of the outer infill leaf with better performing clay units.
Source: Modified based on [93].

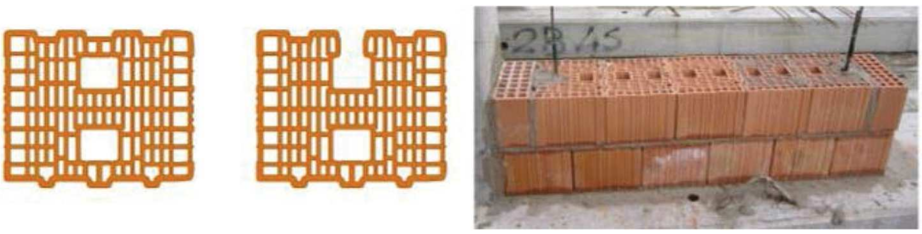


Fig. 16. Replacement of existing envelope by reinforced masonry (RM) infill walls [95] - CC BY 4.0.

cellular polyethylene strips has been explored to isolate infills from steel [102] or RC frames [103]. 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 [104]; who placed elastomers along the sides and top of the infill walls, constructed with highly thermally insulated clay bricks filled with styrofoam. Brick units filled with more advanced materials have also been proposed, such as Phase Changing Materials (PCMs) leading to heat flux reductions up to 10% (e.g.: [105,106] or aerogels (see Fig. 18) achieving a very low U-value of 0.157 W/(m^{2}K) for a wall, but at a relatively steep additional cost of 1000€/m^2 [107].

2.4. 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 [108]. 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 [109]. Timber joists may be less typical, but can also be found in early RC buildings [110], 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 [111]. From a thermal point of view, as with walls and windows, also the horizontal elements of older structures have

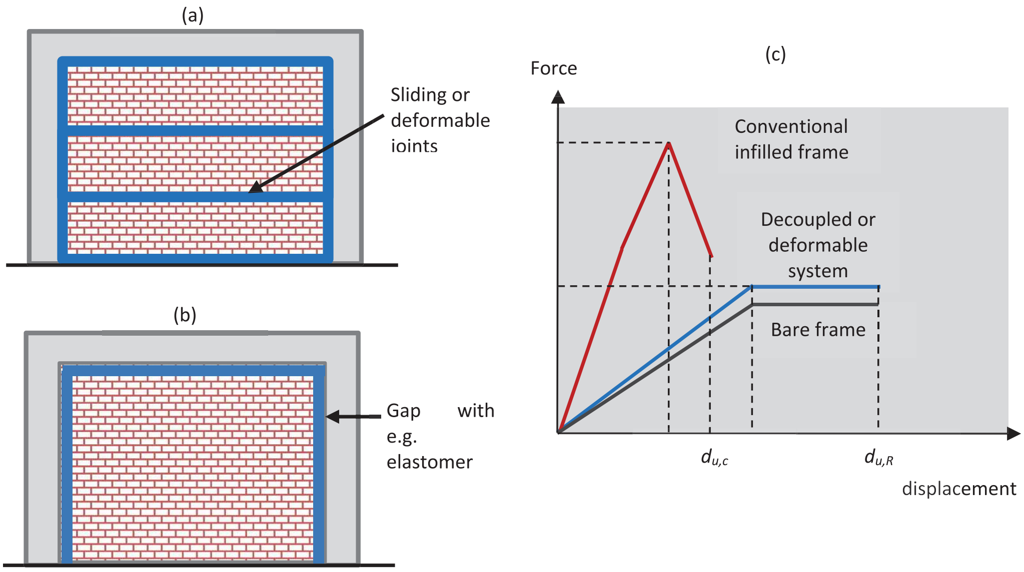


Fig. 17. Replacement with decoupled infills: (a) using sliding joints; (b) provision of a gap; (c) influence on frame behaviour.

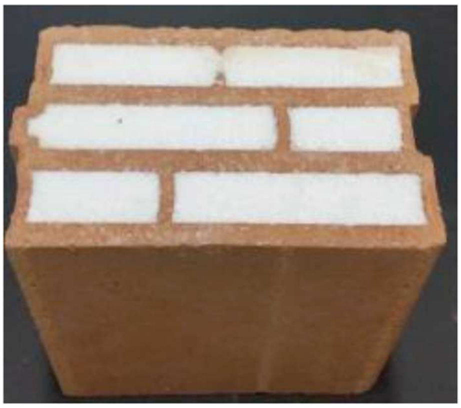


Fig. 18. Aerogel-filled masonry units [107] – CC BY 4.0.

U-values far higher than those of modern buildings. While insulating floors and roof is one possibility, other energy renovation options include ventilated roof systems (e.g.: [112] or radiant floors systems (e.g.: [113].

Interventions on horizontal elements would appear to be particularly compatible, in terms of their invasiveness, spatial overlapping and scale of application (e.g., an extrados strengthening intervention may be connected to the use of insulating panels or radiant floors,

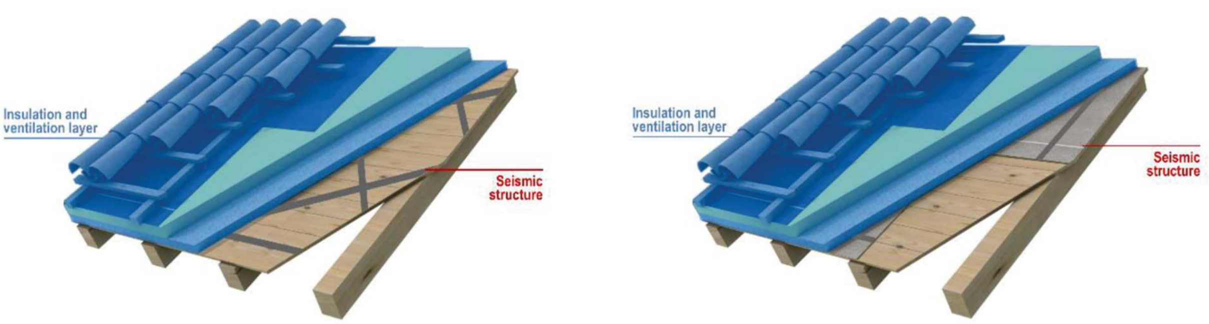


Fig. 19. Schematic views of the thin-folded shell combined with ventilating layer for existing wooden roofs.

whereas an intrados strengthening intervention may be connected to the use of false ceiling and the use of the cavity to install new equipment). Still, *specific* technologies for the integrated retrofitting of roofs or floors have not been sufficiently investigated. In the Nested Building retrofit [80], 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 Fig. 14b). Similarly, the existing roof structure can be demolished and rebuilt or be complemented by an internal CLT plus thermal insulation layer.

For roofs, Giuriani et al. [114] proposed a technique for the recovery of historic wooden roofs. The solution 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. A schematic view of this type of intervention is presented in Fig. 19.

Finally, Basiricò and Enea [115] 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.

3. Analysis of integrated retrofitting technologies

As shown in this review, research into combined seismic and energy retrofitting is a relatively new field, however several different technologies have already been proposed and are currently being tested. To further understand their potential, 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 in Table 1, with different criteria for comparing the retrofit technologies. No comparison between the different technologies in terms of energy performance is offered, as different levels of improvement can be achieved with any of the suggested technologies, depending on the location and amount of retrofitting material applied. For thermal insulation, the improvement in thermal behaviour depends on the thickness and U-value of the provided material, with improvements between 40 and 85% presented in the literature. Additionally, 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 …), to achieve a further improvement in energy performance. In any case, depending on the level of investment, the improvement in energy performance of any of the presented retrofitting solutions may produce a similar level of improvement.

In terms of seismic performance, the lateral load capacity improvements of different technologies are presented in Table 1. Again, no direct comparison between the values reported in the literature should be made, as the application of different structural interventions were for different buildings, and with potentially different performance targets, A range of reported lateral load capacity improvements is however provided here to give a general idea of differences between the different technologies. A qualitative classification of renovation costs is also provided, as a more detailed quantification of retrofitting costs was seen out-of-scope of this review, requiring the analysis of specific benchmark case studies to ensure a fair comparison between different retrofits (e.g. in terms of location, target of retrofitting improvements and building typology). Consideration is also given to the level of invasiveness, considered as the degree to which the existing building appearance and characteristic is affected, hence providing a measure of architectonical and functional impact, and the level of disruptiveness, which reflects the duration of the intervention, business downtime and the necessity for residents' relocation. 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). This comparison is however only **indicative** and is by no means meant as a decision-making tool for selecting retrofitting options. The reader is also referred to an extensive technical report covering further aspects on the identified retrofitting solutions including cultural heritage buildings [116].

3.1. Level of invasiveness and disruptiveness

Based on the work presented in the literature, the level of invasiveness, as well as the disruptiveness of the different interventions is assessed in this section. Solutions with lower level of invasiveness are those that affect the character and appearance of the building the

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

	Lateral load Capacity improvement	Cost of implementation	Level of invasiveness	Disruptiveness	Integration of seismic-energy retrofit [(1)]
Exoskeleton systems	50–100%	Medium-High	High	Low	Coupled/Integrated
Interventions on existing envelope (TRM + thermal insulation)	50–60% in-plane 300–400% out-of-plane	Low	Medium	Low if carried out from the external face	Coupled
Strengthening of openings with steel frame + new window	25–50%[(1)]	Medium	Medium	Medium	Coupled
Timber-based panels with thermal insulation	25–50%	Medium	Medium	Low if carried out from the external face	Integrated/coupled
Replacing of existing envelope	50–100% in-plane 300–400% out-of-plane	Low	High	Medium-High	Integrated
Interventions on floors or roof	10-50 times higher in-plane stiffness	Medium	High	High (Low-medium for roof)	Coupled

[(1)]In this table entry is indicated if the seismic plus energy retrofitting is done by a single element (integrated) or two elements working in parallel (coupled).

least, while the least disruptive interventions affect occupancy the least (e.g. interventions done from the outside only).

Exoskeleton interventions typically lead to the complete modification of a building's façade and hence have the highest architectonical impact (most invasive) of the investigated solutions, hence making them unsuitable for heritage buildings. Conversely, this can be as an architectural renovation tool, improving the aesthetics of building façades, e.g. in the case of post-war RC buildings, and allowing the construction of additional living spaces, balcony and new stories. Despite their invasiveness, exoskeletons minimise the disruption to occupants as they are built entirely from the outside, hence reducing business downtime and potentially avoiding residents' relocation. As additional foundations are built, no works on the existing foundations are required, reducing disruptiveness further. However, 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 [117].

Construction time and labour intensiveness can also be considered lower for exoskeletons than for all other interventions. However, the works required may include interventions on the structure itself at the connections to the exoskeleton (e.g. in the case of weak frame elements, nodes or floors). If standardised connections, modular elements and dry solutions (in the case of steel or precast concrete exoskeletons) can be employed, labour intensiveness can be further reduced, e.g. using precast RC elements or steel sections Exoskeletons may hence be particularly suitable for public buildings, such as hospitals, which require retrofit strategies with very low impact on its use. 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.

For **interventions on the existing envelope**, the invasiveness depends on the operational strategy. For instance, if TRM strengthening can be applied on the external side of existing infill walls only (which also prevents the out-of-plane failure of infills), it avoids downtime and reduces the need for residents' relocation, hence 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, as for exoskeletons, this may actually have a positive impact on the building regeneration from an aesthetic point of view. In the cases were a double-sided TRM intervention is needed, or in the case where the external appearance of the structure cannot be modified, total or partial relocation of residents can however not be avoided.

Similar conclusion can be made for **timber-based or precast panels**, however, the use of prefabricated panels reduces the onsite work and labour time, hence also the associated downtime. The effectiveness of the intervention additionally depends on the reliability of the connection between the panel system and the original structural elements, which may be an issue for older masonry structures, if the substrate quality is very low. In such cases the need for increasing the masonry wall compactness and quality by applying additional strengthening materials needs to be evaluated, increasing the duration of the intervention, costs, invasiveness and downtime, depending on the selected ancillary intervention.

When window replacement is part of a planned intervention, **strengthening interventions on openings** may be regarded as having a medium level of invasiveness. 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, unless a sequential approach is adopted. In such case the building undergoes partial and consecutive downtimes where the works are concentrated to individual floors or units, hence reducing the time for resident relocation and business downtime significantly. If fenestration replacement is however not foreseen, other types of seismic and energy retrofit of the building may be more effective. Crucially, however, the effectiveness of said intervention still needs to be tested further and may be limited depending on the initial state of the masonry walls.

Replacing existing infill walls can be considered more invasive and disruptive then their strengthening, as resident relocation is typically necessary. In cases where it is sufficient to replace only the outer leaf of a masonry infill, the impact of the intervention can be significantly reduced. Still, the replacement of masonry infills requires the demolition of at least one layer of masonry infills, with related disturbance and vibrations, and additionally generates waste, which is very often not recyclable due to the age of the original material. The enhancement of in-plane and out-of-plane capacity, as for strengthening interventions, leads to an increase of lateral stiffness, which can produce not only a decreased deformability of the frame, but also an increased seismic demand to the frame. This in turn may lead to the need for interventions on the RC frame elements and/or on the existing foundations. 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, the disruptiveness and invasiveness of infill replacements may be justified as it additionally will improve the overall building quality and indoor comfort.

Finally, a high level of invasiveness is associated also with interventions on the **horizontal elements** of a building, particularly on intermediate floors. When the intervention is carried out on the extrados, it is generally necessary to remove the existing floor layers and finishing, and to possibly reconstruct existing installations (either electric system or plumbing). When working on the floor intrados, removing the existing finishing layers is typically required instead, 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. If interventions concern the roof only, downtime is reduced and the relocation of residents may be avoided, depending on the presence of an attic floor.

3.2. Environmental impact

To assess the environmental impact of proposed combined retrofitting solutions, 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 need to be assessed [118]. For a more sustainable intervention, particular attention should hence be paid to the choice of materials, both in terms of thermal insulation and structural retrofitting. In Fig. 20, a very basic 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** is calculated based on the quantities (e.g. thickness of panels, sizes of sections) suggested in the individual publications reviewed here-in. The amount of material is then attributed to a 3-storey reference building with 200 m^2 (10 m × 20 m) of floor surface and 3 m of inter-storey height, and results are presented as a normalised value per m^2 of floor area (see Annex). A distinction is made between the embodied carbon of the materials used for structural and energy purposes.

The numbers in Fig. 20 should be considered for illustration purposes only, as the level of strengthening and energy efficiency improvement of the different solutions is not equal. Moreover, next to the environmental impact of the materials used, in a full life-cycle assessment, the embodied carbon of transportation and retrofit construction (along with potential demolition and waste) would also need to be considered. These are however strongly reliant on the country and even specific construction site.

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 [119]. 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.

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 [17]. The environmental impact of seismic risk on the energy refurbishment of a selected RC building case study in Italy was evaluated using annual embodied equivalent CO_2 emissions (ECO_2e) as the corresponding 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.

3.3. Assessments of economic benefits of combined retrofitting

The economic potential of combined retrofitting schemes in regions of moderate to high seismicity has been determined by different research groups. Leone and Zuccaro (2016), assessed the effectiveness of seismic and energy retrofitting using macro-scale simulations of natural hazards in the region of L'Aquila (Italy). In their evaluation, three mitigation scenarios were considered: (a) seismic improvement, (b) seismic improvement along with energy retrofitting that would achieve 25% less consumption, and (c) equal

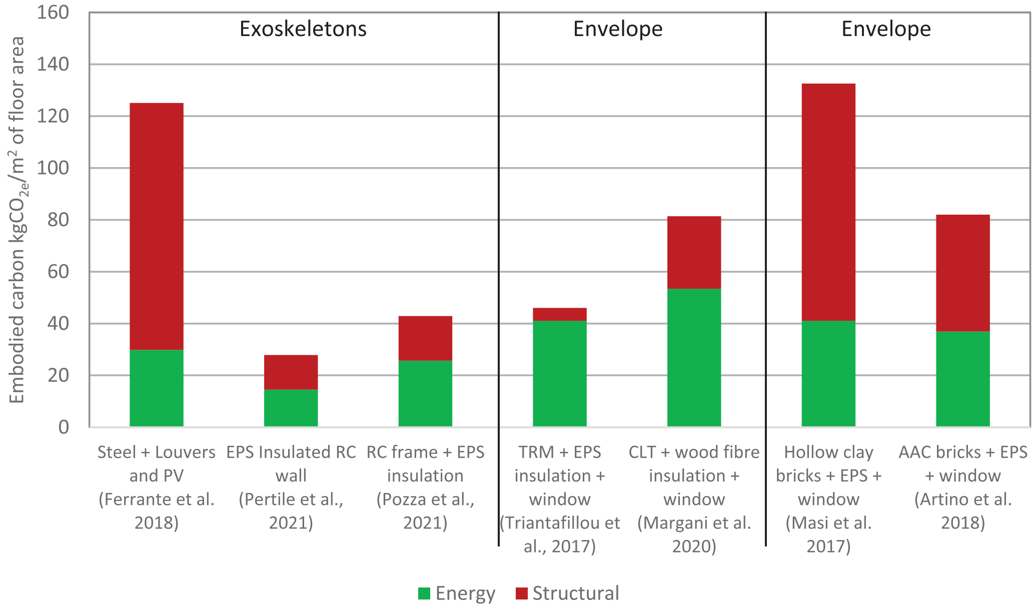


Fig. 20. Simplified assessment of the cradle-to-gate embodied carbon for the materials used in different integrated retrofitting schemes.
Source: Elaborated based on embodied carbon data from the ICE (Inventory of Carbon & Energy) database V3.0–Nov 10, 2019 (https://circularecology.com/embodied-carbon-footprint-database.html).

to (b) but with 50% less energy consumption, finding that the latter scenario would result in the fastest payback time.

To facilitate the implementation of combined retrofitting schemes, next to adequate materials and technologies, there is a need for a combined economic evaluation method to understand the cost-effectiveness of different renovation options. One such common economic approach for assessing the efficiency of the seismic and energy resilience of an existing structure was introduced by Calvi et al. [18]. Calvi et al. defined a common financial decision-making metric called **Expected Annual Loss** (EAL). EAL is usually defined as a ratio of the annualised cost divided by the value of the existing building, broken down into the parts related to energy consumption (EAL_E), and the EAL due to seismic losses (EAL_S) for countries located in seismic areas. Therefore:

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

In terms of annual energy losses, EAL_E, the evaluation is typically a straightforward task, where the energy consumption of a building is assessed (e.g. through BEM) and is translated to an annual cost by using local energy costs. For the seismic loss evaluation, instead, a probabilistic framework is used, e.g. that of performance based earthquake engineering (PBEE) [120]. In this probabilistic analysis, annual seismic losses are calculated by integrating building-specific vulnerability functions with seismic hazard curves to obtain loss-exceedance curves.

Such an approach based on a probabilistic framework for seismic loss estimation was applied by Mastroberti et al. [45] who used analytical fragility curves for the seismic assessment of the economic feasibility of various combined seismic and energy retrofitting interventions, including the addition of RC walls or the TRM-strengthening of masonry infills, with additional energy retrofitting through the use of expanded polystyrene (EPS), polyurethane (PUR), aerogels and/or new windows. The combination of 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. This system (TRM + polystyrene insulation) was also evaluated by Bournas [27] and Gkournelos et al. [121] using a simplified EAL-based procedure, highlighting that the integrated retrofitting system was more cost-effective compared to an energy upgrade solution alone, especially for structures with higher seismic risk. Recently, Pohoryles et al. [52] studied that same retrofitting scheme for five different building typologies (2 masonry and 3 RC) across twenty European cities located in areas of different seismic hazard (five seismic zones) and climatic conditions (four climatic areas). Again, a methodology based on PBEE was used for evaluating seismic losses, while the energy losses were assessed through BEM. By calculating the EAL for seismic and energy losses, a combined evaluation of different renovation option was carried out. In line with previous findings, the integrated approach was found to have shorter payback times in cases of medium to high seismicity than a simple energy retrofit.

While a more detailed analysis of methods for the assessment of integrated retrofitting schemes is out of the scope of this study, the reader is referred to a recent study by Menna et al. [122]; which presents an overview of assessment methods for the seismic and energy performance of existing and retrofitted buildings. The review highlights the importance for further developments of fully holistic design and assessment frameworks that also include full life-cycle assessments. Similarly to existing cost optimisation tools in Building Information Models (BIM) for energy (e.g.: [123] and seismic retrofitting [124,125], future research is needed to integrate holistic retrofitting assessment frameworks with life cycle cost assessments in BIM-based approaches.

3.4. Financial, social and cultural barriers to combined retrofit interventions

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 initial costs of building retrofit investments are an overwhelming barrier for many owners, even for measures that are cost-effective in the long term. Return on investment regarding energy efficiency measures is more straightforward than in the case of seismic retrofitting, where savings are associated with the probabilistic nature of seismic risk, i.e. not giving a tangible financial incentive to renovation. In many cases those living in dwellings with poor seismic and energy performance are low-income households, i.e. the least able to invest in renovation measures [126]. If the dwelling is not owner-occupied, a further barrier is the so-called "split-incentive"/"landlord-tenant dilemma", as the expected savings might not be significant for the landlord because only tenants benefit from lower energy costs or increased living comfort and safety. Moreover, multi-family houses constitute a significant proportion (>60%) of dwellings in some of the EU's most seismic countries as Greece or Italy [127], leading to the further obstacle of finding consensus on the retrofit expenditure [126].

To achieve a higher uptake of renovation, incentives including public funding are needed to overcome these financial barriers. To promote building renovation, fiscal incentives, such as tax deduction, tax credits and VAT reduction, may be the most effective measure, to encourage private investment in seismic and energy efficiency retrofitting [126]. A prominent example are the *Eco-Sisma Bonus* systems for renovation works in Italy, [128,129] which were recently increased to an even higher tax credit share of 110% in the framework of the economic relaunch after the COVID-19 pandemic, through the *Superbonus* scheme [130]. Note however, that the focus of the renovation incentives still heavily relies on the energy performance improvement only, potentially ignoring the risk of seismic losses.

Next to financial barriers to combined renovations, another aspect not to be overlooked is the insufficient awareness of building owners and tenants about the seismic vulnerability of their dwelling [126]. While an inadequate energy performance is often known to the tenant or owner due to increased energy costs, or through an energy performance certificate system, seismic risk and risk mitigation awareness is often low, even in regions of high seismic hazard, unless a strong earthquake occurred recently [131].

To attract more building owners to carry out integrated upgrading interventions, together with adequate funding mechanisms and policy measures, social awareness campaigns at the national and European level are hence required. Examples of national campaigns to raise awareness can be found for instance in Italy. The campaign "I do not risk" [132] is an Italian national communication campaign on seismic risk, increasing collective and individual responsibility and participation to risk reduction strategies. Another example is the "Diamoci una scossa" campaign [133], in which architects or engineers with expertise in seismic risk carried out free visits to residential buildings in order to advise tenants on the seismic vulnerabilities of their building. Additionally to information on seismic risk, the benefits of integrated renovations need to be communicated through adequate channels [126]. As an example, the e-SAFE project not only concentrates on developing technical solutions for integrated retrofitting, but also aims to overcome social barriers by developing a multi-scale stakeholder forum, with the aim of engaging different stakeholders and raise public awareness through co-design processes [84]. Finally, information campaigns and trainings are also required for professionals in the building renovation industry.

4. Conclusions

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 an integrated approach to building renovation. This is of high relevance to current policy measures in the fields of energy renovation of buildings, circular economy principles within the construction sector, improving the resilience to natural disasters, as well as protecting our built heritage.

Combined and integrated seismic and energy retrofitting of buildings has been increasingly investigated in the scientific literature from both, a theoretical and an experimental, point of view. The present study provided a state-of-the-art review and analysis of integrated techniques for the seismic and energy upgrading of EU buildings. Integrated retrofitting interventions can be divided into four different broad groups: (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. An analysis and comparison in terms of their costs, level of invasiveness and business downtime related to the retrofitting implementation, as well as the environmental impact of the materials used, was then provided.

Research into **exoskeleton solutions** includes fully integrated shell-type solutions, starting from simple BRB-braces combined with solar shading, to material-efficient diagonal steel grids (diagrids) integrated with various thermal panels (BIPVs, shading or thermal insulation). Auxiliary structures made from 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 permanent 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 can be deemed highly invasive, changing the external appearance of a structure completely. In the context of the New European Bauhaus this may be a desirable feature, as the exoskeleton can provide an architectural upgrade. As the interventions can be done entirely from the outside, occupant disruption is additionally reduced. The cost and environmental impact of exoskeleton solutions are however typically higher, particularly in the case of steel-braced solutions, and the construction of additional foundation systems may be limited by the lack of space in crowded urban environments.

Rather than constructing external auxiliary structures the existing structure can be upgraded through **integrated interventions on the existing building envelope**. This may for instance be achieved through strengthening of external walls with composite materials (in particular TRM) combined with thermal insulation, applied within the same intervention. Such combinations can be considered the most mature of all presented integrated retrofit options, as several experimental validations of the seismic-plus-energy system have been carried out, highlighting their effectiveness 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 may have the potential of future applications of a single material for structural and thermal upgrading, but to-date no solution with thermal mortars can provide adequate strength and thermal resistance. As for exoskeletons, TRM-based integrated retrofitting brings the advantage of external application and low disruptiveness, but it additionally provides better compatibility with masonry structures and very high cost-effectiveness and low environmental impact. Developments in **prefabricated panels** based on TRM or TRC, integrated with thermal insulation or capillary tubes, have also been presented as well as engineered timber-based panels with thermal insulation. The advantage of prefabricated panels over the wet layup of TRM retrofitting includes reduced construction time, increased modularity and the potential for full integration of the structural and energy elements. Finally, 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.

Another avenue is the **replacement** of the external walls of masonry-infilled RC buildings with (1) stronger and more thermally insulating bricks; or (2) 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 filled with thermal insulation material may improve their energy efficiency and sustainability. While replacing the external envelope is extremely invasive and disruptive, the costs associated with the intervention are typically low.

Finally, regarding **integrated interventions on horizontal elements** (roof and floors) only limited proposal can be found in the literature, even though the combination of seismic and energy interventions could have a high potential for integration. The so-called Nested Building, providing a new inner shell for improving the seismic performance and energy efficiency of (historic) masonry buildings, which included the replacement of existing floors with CLT boards and to apply CLT panels and thermal insulation at the roof level. Other examples include the provision of a structurally-sound roof structure integrated with a secondary ventilating structure.

Finally, from a technical point of view, the readiness of integrated retrofitting solutions is still questionable in many cases. Most often the combined seismic and energy purpose of those interventions has emerged only very recently, and there is still a lack of comprehensive works that tackle the two aspects together, in an integrated evaluation. To date, only limited technologies have been tested experimentally as combined or integrated solutions, such as the experiments on TRM + thermal insulation, while in most cases the seismic performance and energy efficiency improvements have been tested separately and their integration has only been assessed through numerical models. Still though a number of **economic feasibility studies** the potential economic benefits of combined retrofitting has been demonstrated in at least moderately seismic regions of Europe.

Despite reduced payback times, given the initial costs of interventions, financial barriers 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Annex: Calculation of environmental impact

The calculation of the environmental impact is performed for a 3-storey reference building assuming 200 m^2 (10mx20 m) 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** are taken from the latest version of the ICE database (V3.0–Nov 10, 2019),[1] as shown in Table 2. 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 2
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–Nov 10, 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. 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 (0.9 × 1.2 m) in each one out of two frames. For the steel exoskeleton, a combination of photovoltaics, green walls and

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

louvers is assumed to cover the envelope in equal quantities. The calculation is summarised for each of the interventions in Table 3.

Table 3
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 [49]	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 [53]	Mortar (2 mm 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 [93]	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 [94]	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 [76]	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 [37]	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 [46]	3 RC columns (250 mm × 250 mm)	0.063m^2 (section)	0.56	139.1	8.3
	RC cross-beam (300 mm × 400 mm)	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.

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