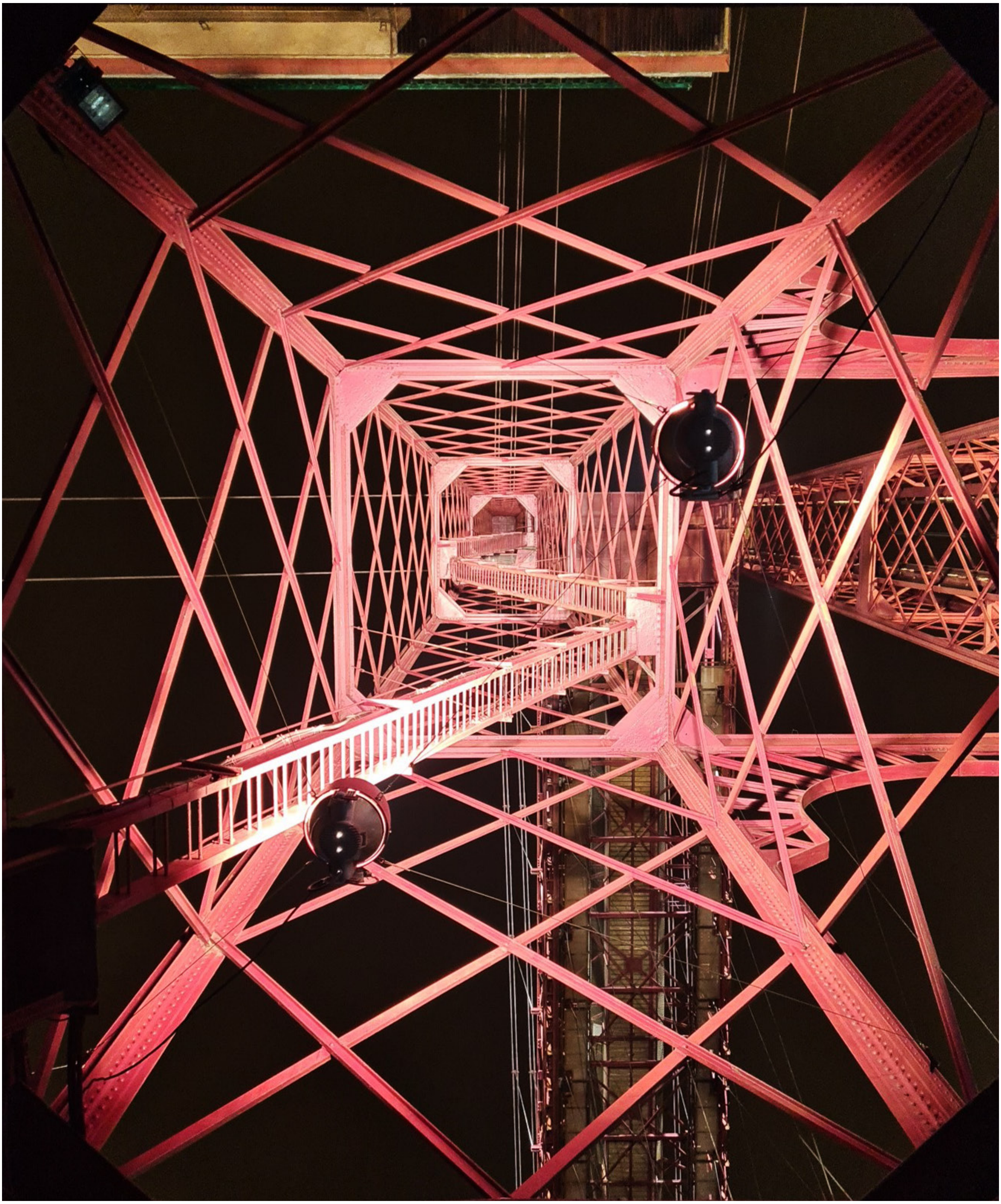

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TECHNOLOGICAL ANALYSIS OF A PREFABRICATED TIMBER-BASED SYSTEM FOR THE INTEGRATED RENOVATION OF RC FRAMED BUILDINGS

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Abstract

Most of the building stock in European seismic countries is highly energy-intensive and earthquake-prone since it was built before the enforcement of effective energy and seismic codes. Renovation actions that synergically integrate both energy-efficient and anti-seismic interventions are strongly needed in these countries. However, the implementation of such interventions is currently limited by barriers that are mostly related to the high cost and invasiveness of traditional seismic retrofit techniques.

A new holistic design approach to the building renovation is required to overcome these barriers. This should result in innovative and integrated retrofit interventions able to specifically meet the needs of cost-effectiveness, quick installation, reduced users' disruption, and low environmental impact.

In this framework, the use of cross-laminated timber (CLT) has been recently investigated for retrofit purposes in light of its good mechanical and physical performance.

In this research context, this paper illustrates a novel timber-based retrofit technology for RC framed buildings developed within the e-SAFE H2020 project. This technology consists of cladding the external building envelope with a new prefabricated timber-based shell that acts as seismic-resistant and energy-efficient skin, also contributing to renovating the architectural image of the building. The new skin combines structural CLT-based panels – equipped with novel devices for seismic energy dissipation – with non-structural wooden-framed panels.

Specifically, this paper presents a construction analysis of the proposed retrofit technology, investigating its technical feasibility, versatility, and potentialities, as well as possible application limits.

Keywords

Timber-based panels, Cross-laminated timber, Prefabrication, Seismic and energy renovation, Friction damper.

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1. INTRODUCTION

In European seismic countries, a recent issue in the building renovation sector is the need to combine the energy-efficient measures promoted by the current environmental and energy policies with anti-seismic interventions. Indeed, the building stock designed without energy-efficient and anti-seismic criteria is extremely wide in these countries, mainly including masonry or reinforced concrete (RC) framed buildings [1].

At present, roughly 75% of the EU building stock is energy inefficient [2], thus contributing to the increase in greenhouse gas emissions and, consequently, climate change and related natural hazards. At the same time, the strong earthquakes that occurred in Europe in the past decades demonstrated the high level of seismic vulnerability of the building stock and the catastrophic consequences that the damage or collapse of buildings can entail. For instance, in the last 50 years in Italy alone, earthquakes caused around 5000 deaths and over €180 billion in monetary losses, destroying a considerable portion of the affected building stock [3]. Furthermore, the recent earthquakes that occurred in Italy (i.e., L'Aquila 2009, Emilia 2012, Amatrice-Norcia-Visso 2016), have seriously damaged several buildings previously subjected to only energy efficiency interventions, frustrating these interventions and the related economic investment. The environmental impact in terms of the carbon footprint associated with buildings repair or reconstruction after a seismic event is also relevant. In particular, the expected annual embodied equivalent CO_2 associated with seismic risk has been estimated equal to 87% of the annual operational CO_2 after only energy retrofitting interventions [4]. The framework depicted above evidences that in earthquake-prone countries, energy-efficient and anti-seismic renovation interventions must be synergically combined in order to: 1) prevent human and economic losses caused by seismic events; 2) reduce buildings damage in case of earthquakes and avoid the environmental impact associated to their repair or reconstruction; 3) avoid doubling several costs in case of implementation of the two retrofit interventions in distinct periods (e.g., for building-site setup, demolition works, scaffolding, renders and finishings, etc.) [5, 6]; 4) increase the living comfort and safety of the occupants; 5) enhance the building value; 6) extend the building lifetime.

However, several barriers currently hinder the combination of seismic and energy renovation actions. On the one hand, there is a lack of attractive, cost-effective, and low-disruptive technical solutions. Indeed, the most common seismic upgrading techniques are very expensive and highly invasive, requiring a long time for implementation, the interruption of the building operativity, and the occupants' relocation during the works, often for several months [7]. On the other hand, the building renovation is also hindered by social and cultural barriers, mainly due to the insufficient spread of seismic risk culture and environmental protection culture. In particular, the poor or partial knowledge of the seismic risk often leads to the low propensity of building owners to prioritise the adoption of anti-seismic interventions.

New holistic approaches to building renovation have been recently investigated to overcome the main technical and economic barriers. In particular, some studies have examined evaluation methodologies for combining current structural and energy retrofit techniques [8, 9]. Other studies have been focused on the development of novel integrated retrofit solutions that can be able to meet the current needs of cost-effectiveness, quick installation, and reduced disruption for users [10–13].

In this framework, wood has shown great potential as a sustainable and renewable retrofitting material to upgrade the seismic and thermal performance of buildings, thanks to the recent advancement of engineered timber products, such as cross-laminated timber (CLT), as well as wood-based insulating materials.

In this regard, this paper firstly presents a state-of-the-art review of the topic of CLT-based retrofit technologies for RC framed buildings. Then, the paper describes a novel integrated retrofit solution that has been recently proposed by Margani et al. [14], and is still under development within the Horizon 2020 innovation project called e-SAFE (Energy and Seismic AFfordable rEnovation solutions). This solution consists of cladding the external envelope of the building with structural and insulating prefabricated timber-based panels. Specifically, this work presents a construction analysis of this retrofit solution to investigate its technical feasibility, versatility, and main technical requirements. The potentialities and limits of the application of the proposed technology are also examined to evaluate its replicability.

2. STATE-OF-THE-ART REVIEW OF CLT-BASED RETROFIT TECHNOLOGIES FOR RC FRAMED BUILDINGS

CLT is a plate-like engineered timber product consisting of an uneven number of timber board layers (usually ranging from three to five, but even more), which are arranged crosswise to each other at an angle of 90° and are connected by adhesive bonding. The result is a rigid composite element having high mechanical performance. In fact, the crosswise build-up provides the CLT panel high capacity of bearing loads both in-plane and out-of-plane, allowing its application as a full-size wall and floor element. The engineered CLT configuration also minimises swelling and shrinkage rate, providing the panel with high dimensional stability in-plane [15]. Furthermore, CLT is a bad heat conductor thanks to its low thermal conductivity (0.10 ÷ 0.13 W m^{-2} K^{-1}), with good thermal insulation and thermal inertia properties. The high mechanical and physical performance, the good environmental properties as well as the high level of prefabrication of the CLT have promoted its rising spread, as attested by the growing number of residential and office buildings worldwide, with a growth of the production capacity rate of 15÷20% per year [16].

In recent years, the increasing attention to environmental sustainability has led the research community to investigate the building renovation sector as a further application field for CLT. Specifically, recent studies investigated the use of CLT walls as strengthening elements to increase the seismic performance of the existing buildings, with potential results in terms of improvement of the strength and stiffness capacity under seismic loads. The advantages of such potential use are the low increase of the building mass compared to other seismic upgrading techniques, thanks to the low density of CLT, and the benefits of dry installation, such as quick and easy implementation and materials recyclability. The insulating properties of CLT, in combination with additional insulation layers, can also improve the thermal performance of the building in view of an integrated and sustainable approach to the building renovation. The high level of prefabrication of CLT also makes it much more attractive for retrofitting uses, making the industrialisation of the building renovation sector one of the main future challenges.

Different applications of CLT walls to the existing RC framed building have been investigated for retrofit purposes.

First works on this topic have been carried out by Sustersic and Dujic [17], who proposed a low invasive retrofit solution consisting in applying a new outer CLT-shell to the external envelope of the building by realising the connection between the panels and the RC structure through special steel brackets provided of ductility and energy dissipation capacity. The external application of CLT panels has also been investigated within the AdE-SA project [18], resulting in a real application in a case study. The Adhesa system uses dissipative connections with out-of-plane bending capacity and provides for cladding the CLT panels on-site with insulation and finishing materials. Conversely, a totally prefabricated CLT shell has been proposed by the Italian company Wood Beton S.p.A., which has recently introduced the "Rhinoceros-wood" system in the building market [19]. However, its application is currently limited to buildings up to a maximum of three storeys that require a low stiffness increase since the improvement of the building seismic performance is provided only by the strengthening actions of the CLT panels.

One more CLT application includes the use of CLT panels as infill shear walls [20, 21]. Specifically, Stazi et al. [20] analysed the elastic and post-elastic in-plane shear behaviour of CLT specimens, while Haba et al. [21] investigated shear walls composed of narrow CLT elements bonded to each other and onto the RC frame with epoxy resin, achieving possible results in terms of improvement of stiffness, strength and ductility capacity of the structure. Different arrangements of CLT panels, both to the outside of the building or in replacement of the external masonry wythe, have also been proposed by Smiroldo et al. [22]. Then, a low-damage and low-invasiveness retrofit alternative has been recently investigated by Sandoli et al. [23], who proposed using post-tensioned, re-centring, and dissipative rocking CLT walls in the external perimeter of the buildings.

The recent and rich literature on the topic of buildings retrofitting through strengthening CLT walls shows that these solutions are of great interest and highly topical, even if they are still at a preliminary stage. In particular, the use of dissipative devices as connection systems between the CLT panels and the building envelope has a high potential to increase the effectiveness of this solution thanks to the dissipation of a part of the seismic energy, thus reducing the displacement demand of the building structure. Overall, the dampers investigated so far have been mainly conceived to allow seismic energy dissipation by exploiting their ductility capacity. This dissipation mode is less effective in terms of technological and operational efficiency since it requires replacing the dampers and removing the CLT panels after the seismic event.

Based on the above, further investigations on the versatility and practical replicability of CLT-based retrofit technologies, as well as more effective dissipative connections between the CLT panels and the existing building envelope, are required.

3. THE RETROFIT TECHNOLOGY

3.1. MATERIALS AND COMPONENTS

The proposed retrofit technology consists of cladding the external envelope of RC framed buildings with a new prefabricated timber-based shell that acts as seismic-resistant and energy-efficient skin, also contributing to renovating the architectural image of the building. The new skin combines structural CLT-based panels (called e-CLT) fixed to the existing RC frame through novel devices for seismic energy dissipation, with non-structural wooden-framed panels (called e-PANEL), which integrate high-performing windows that replace the existing ones (Fig. 1).

In terms of seismic performance, the e-CLT aims to increase the seismic and dissipative capacity of the existing structure by exploiting the high mechanical properties of CLT and the additional energy dissipation source, respectively. The effect of these multiple features is the reduction of the story drifts caused by the seismic excitation, i.e. the improvement of the seismic resilience of the building.

In terms of energy performance, e-CLTs and e-PANELs integrate insulating materials to increase the thermal resistance of the existing walls, thus reducing the energy demand of the building for space heating and cooling.

Both panels are conceived to be prefabricated off-site and installed from the outside of the building through mobile lifting equipment. The use of prefabricated components and the external dry installation avoid demolition interventions and the occupants' relocation during works, thus significantly reducing implementation costs and time and minimising waste production.

A detailed description of the e-CLT and e-PANEL is reported in the following sub-sections.

3.1.1. THE E-CLT COMPONENT

The e-CLT panel (Fig. 2) is the structural component and has the primary role of reducing the seismic vulnerability of the building. It consists of a prefabricated CLT-based panel and is applied to the outer blind walls of the building. Each e-CLT is equipped with energy dissipation devices that connect it to the beams of the existing RC framed structure. The non-linear behaviour of this seismic

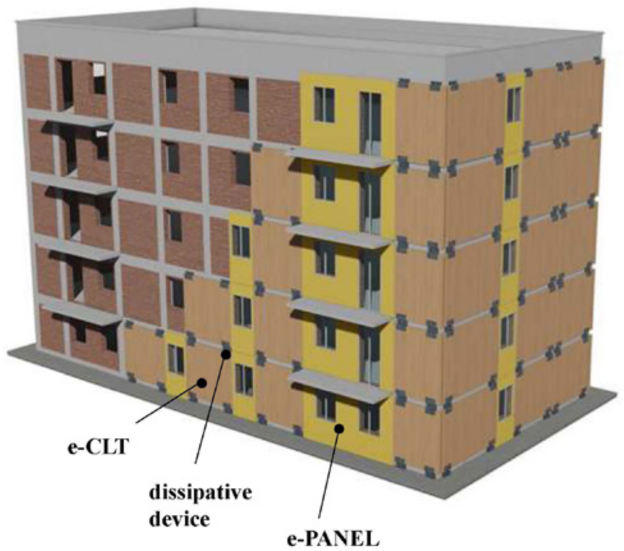
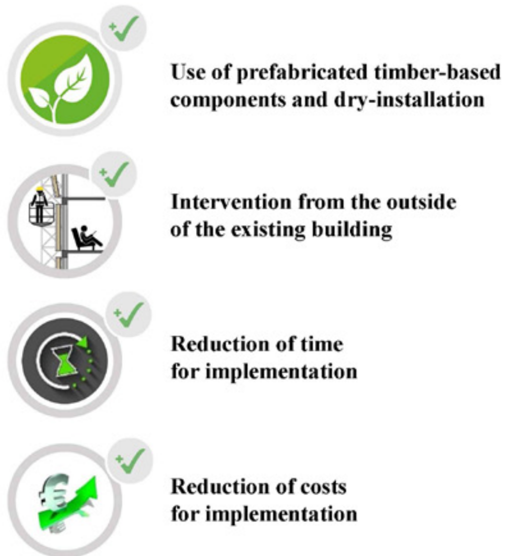


Fig. 1. *Concept of the proposed retrofitting technology.*



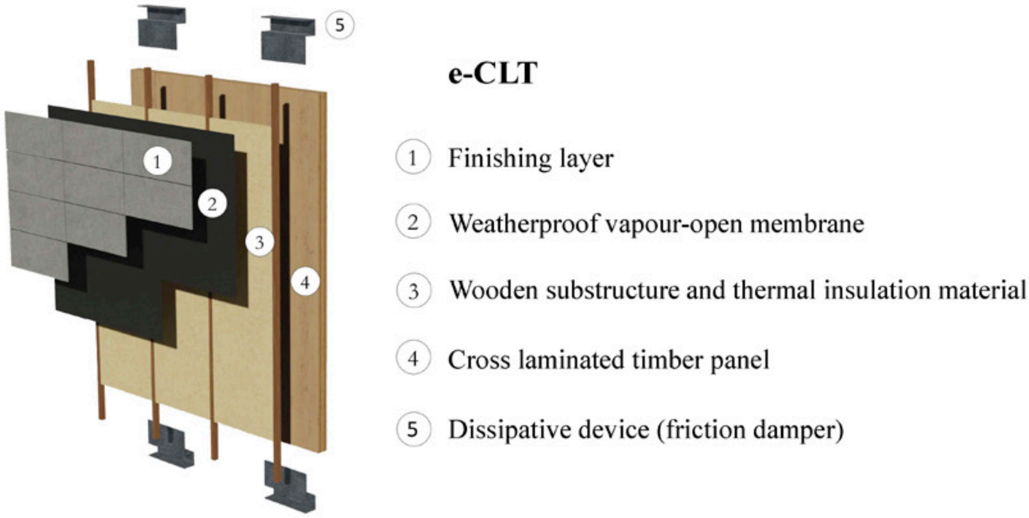


Fig. 2. *e-CLT component.*

upgrading technology is concentrated on the connection devices to protect the CLT panels from damage. In fact, in case of moderate ground motions, the CLT panels increase the seismic capacity of the structure, while in case of stronger ground motions, the friction dampers dissipate part of the input seismic energy, thus reducing the seismic demand of the structure. This further resource of the system reduces the damage to structural components and the possibility of collapse. The size and number of the e-CLTs are defined in accordance with the seismic deficiency of the building and the assumed target performance.

Each e-CLT integrates: 1) a layer of thermal-acoustic insulation material; 2) a weatherproof vapour-open membrane and Ethylene-Propylene Diene Monomer (EPDM) soft bands to prevent rainwater leakage and condensation problems; 3) a finishing layer.

The seismic dissipation device has been conceived to dissipate seismic energy by friction to meet the need for structural efficiency even after seismic events. Indeed, friction dampers overall have one of the most efficient and damage-free energy dissipation mechanisms, without degradation of their resistance and energy dissipation capacity over time.

Figure 3 shows two configurations of the friction damper, which are currently under development [24, 25].

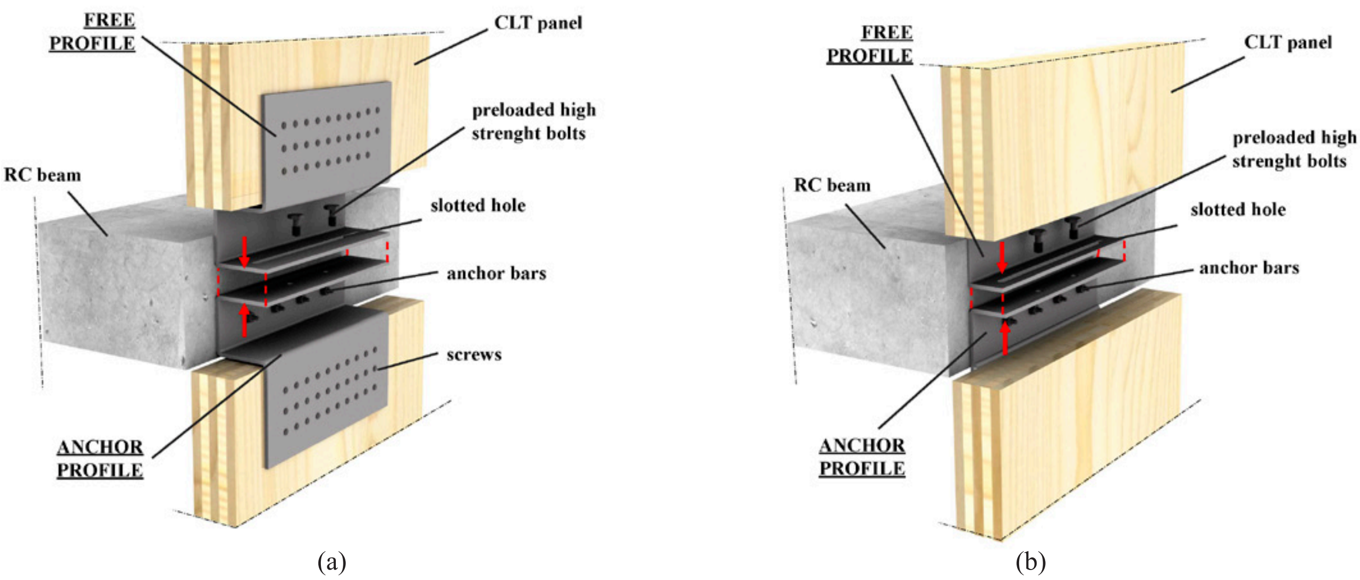


Fig. 3. *Friction damper configurations: (a) multiple-bended configuration with CLT-steel connection on the external side of CLT; (b) single-bended configuration with CLT-steel connection on the internal side of CLT.*

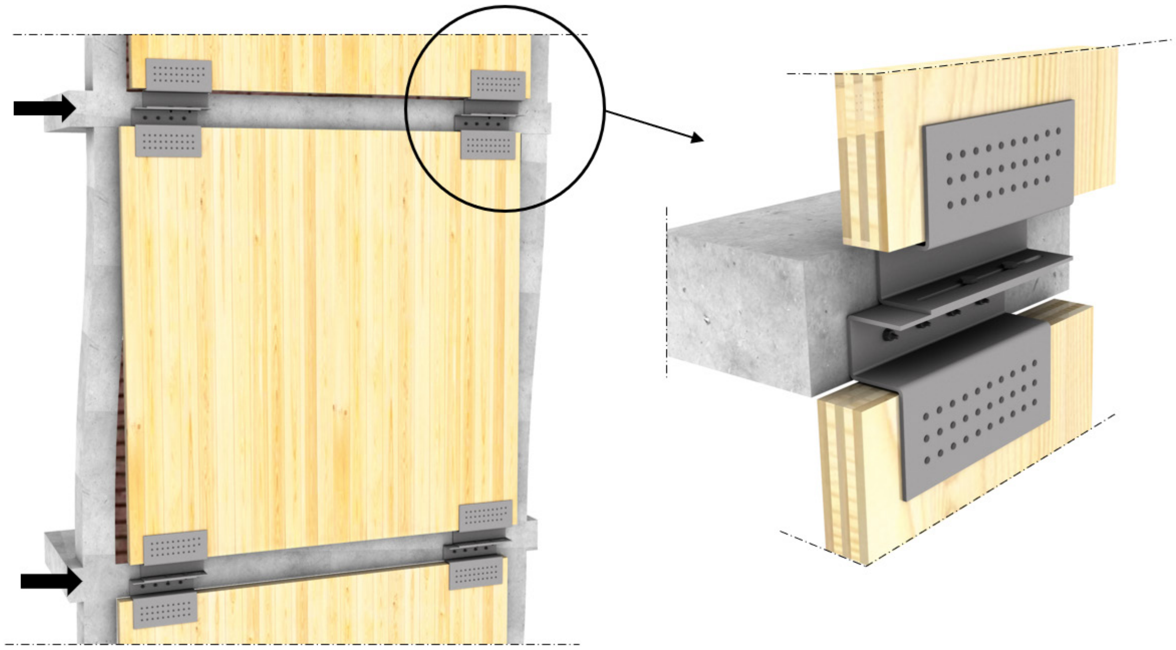


Fig. 4. *The behaviour of e-CLT in the event of dampers activation.*

In both configurations, the damper consists of two press-bended steel profiles that connect the CLT panels of two consecutive storeys. One profile, called “anchor profile”, is connected to the RC beam by anchors for concrete. The other profile, called “free profile”, is provided with a slotted hole and is connected to the “anchor profile” by preloaded high strength bolts. Standard timber screws connect the two steel profiles to the CLT panels. The difference between the two configurations of the damper concerns their geometry. In particular, one configuration (Fig. 3a) is multiple-bended and provides the connection to the CLT on its external side. On the other hand, the other geometry (Fig. 3b) is single-bended and provides the connection to the CLT on its internal side. Overall, the shear force is transmitted between the two profiles by means of the friction exerted on the contact surfaces. During an earthquake, when the force transmitted by the damper attains the value of the friction force, the “free profile” of the damper slides on the “anchor” one thanks to the slotted hole, thus dissipating seismic energy (Fig. 4).

The two dampers have been investigated to evaluate their behaviour under cyclic load. More details on the numerical and experimental investigations regarding these damper configurations can be found in [25]. Further experimental studies are ongoing to optimise the damper geometry.

Overall, the activation of the damper by a predefined force allows controlling the internal forces on both the damper components and the CLT panels, which are dimensioned to limit or avoid their damage and consequent replacement after a seismic event. The length of the slotted hole should also be designed in accordance with the maximum allowable lateral drift of the building to avoid the shear failure of the preloaded bolts before the RC structure could exploit its maximum drift capacity. Furthermore, on an industrial scale, the proposed geometries of the damper facilitate their manufacturing process since the profiles are produced by cutting, drilling, and press bending of steel sheets. These are common processes in metal parts factories, thus increasing the potential commercial success of the damper.

3.1.2. THE E-PANEL COMPONENT

The e-PANEL (Fig. 5) is combined with the e-CLT to complete the new prefabricated envelope by retaining an aesthetic uniformity. It is applied to the outer windowed walls of the building and integrates new high performing windows (multiple glazing with inert-gas filling, thermal-break frames or wooden frames, low-emission coatings, etc.), which replace the existing ones. The new windows can be equipped with external sun shading sys-

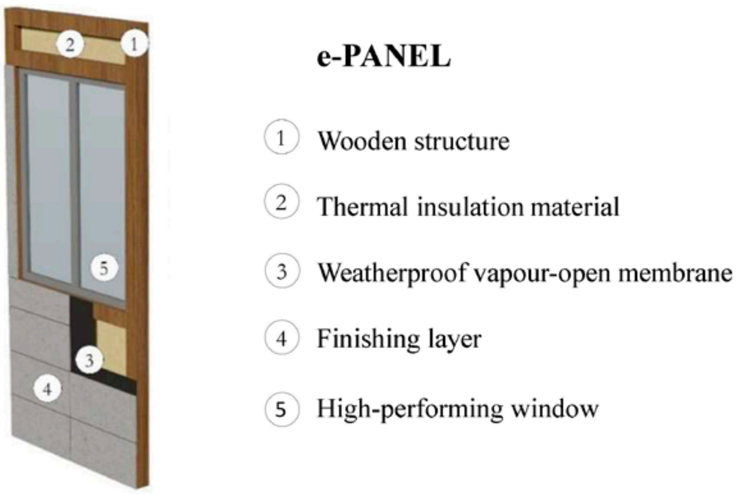


Fig. 5. *e-PANEL component.*

tems (e.g., Venetian blinds, roller shutters etc.) to reduce indoor overheating in summer.

Since the e-PANEL has no structural role, it is made of a lightweight wooden frame to ensure easier manufacture, low environmental impact, and cost savings.

The e-PANEL integrates an insulation layer, a weatherproof vapour-open membrane, and a finishing coating, as much as the e-CLT. A non-ventilated air cavity between the insulation and the cladding layers can be required to match the overall thickness of the e-CLT.

3.2. CONSTRUCTION ANALYSIS

The proposed retrofit technology is characterised by a high level of prefabrication, which makes its implementation fast and easy. Indeed, the panels are entirely prefabricated and are installed through mobile lifting equipment (cranes, lifting platforms, etc.), which avoid the disruption of traditional scaffoldings (Fig. 6).

The installation of the panels takes place from the ground storey of the building to the top one, and from the right corner to the left (or vice versa). Specifically, the e-CLTs are connected to the RC beams through the "anchor profiles" of the friction dampers. These profiles are pre-assembled on the top side of each e-CLT. An additional steel plate between the beam and the profile is provided to ensure the vertical alignment of the e-CLTs and also cover the gap resulting from the removal of the finishing layer of the beam for a higher profiles grip.

Once the e-CLTs of two consecutive storeys are installed, each "anchor profile" is connected to the corresponding "free profile". Based on the damper configuration, the "free profiles" can be installed on-site (Fig. 6a) or can be pre-assembled on the bottom side of each e-CLT (Fig. 6b). The first option allows to properly align and connect the friction surfaces of the two steel profiles, but it requires more time to tighten screws on-site. Conversely, the second option makes the installation process faster, but more prone to errors since the alignment of the friction surfaces cannot be guaranteed on-site. In this regard, additional alignment components are under investigation to avoid installation errors.

Unlike the e-CLTs, the e-PANELs are not equipped with friction dampers since they do not have a structural role, but they are connected to the building structure through steel connectors with seismic resistance properties (Fig. 6). Specifically, the e-PANELs are fixed at the top through commercial angle steel brackets, while specific sliding connectors are provided at the bottom. In this way, they undergo the same sliding movement as the e-CLTs in case of damper activation, while their out-of-plane rotation is avoided.

The e-CLT and e-PANEL are not connected to each other to avoid the transmission of forces from the structural panel to the non-structural one, which could damage the latter.

After the e-CLTs and e-PANELs installation, cladding solutions to cover the dampers are required. These solutions must be easy to install and remove for damper

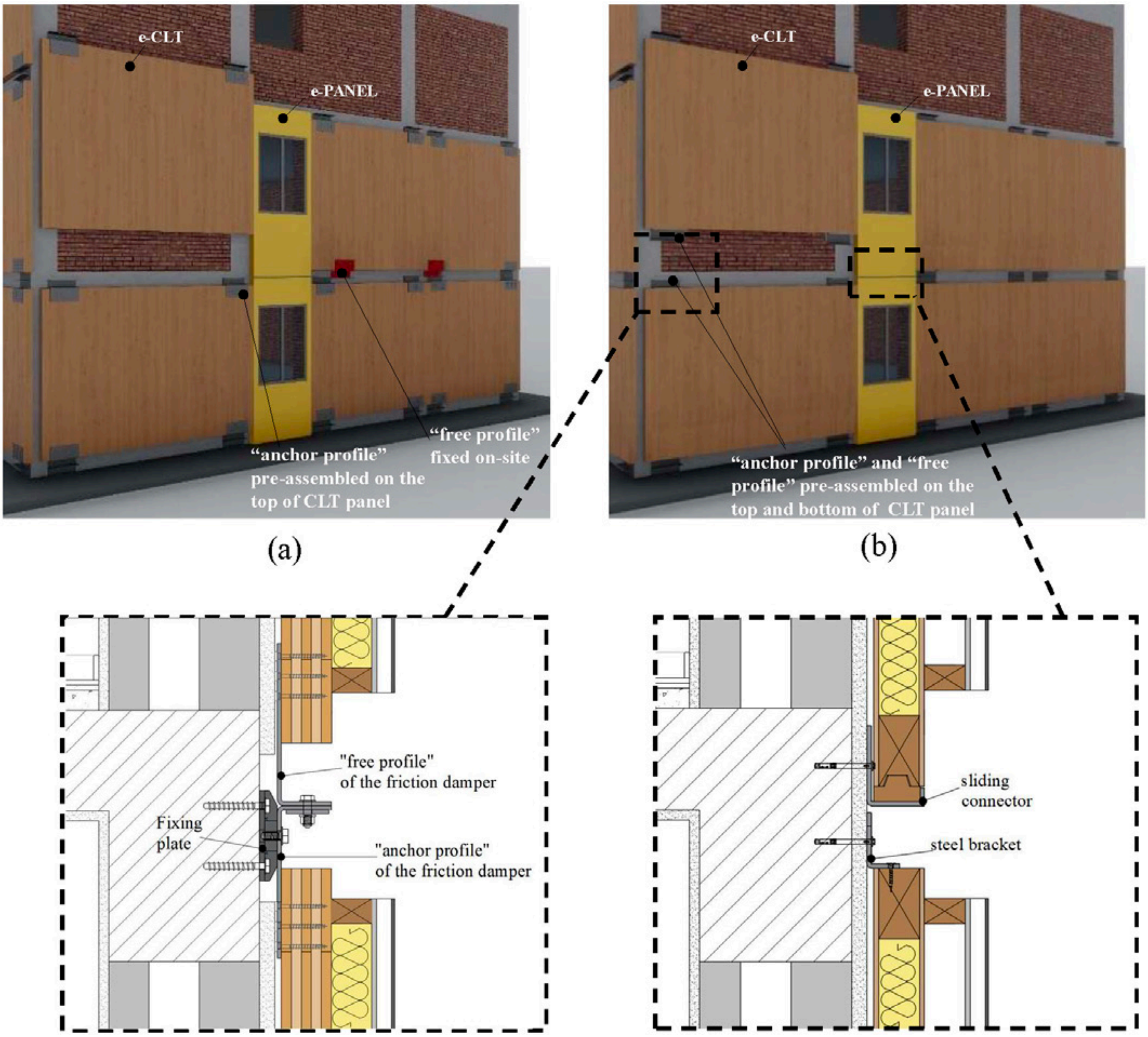


Fig. 6. *Scheme of installation of the proposed retrofit technology in case of damper connection (a) on the front side and (b) on the back side of the CLT panel.*

inspection and maintenance (e.g., preload friction bolts that may have loosened after a seismic event). They also need to reduce the thermal bridges at the beams level.

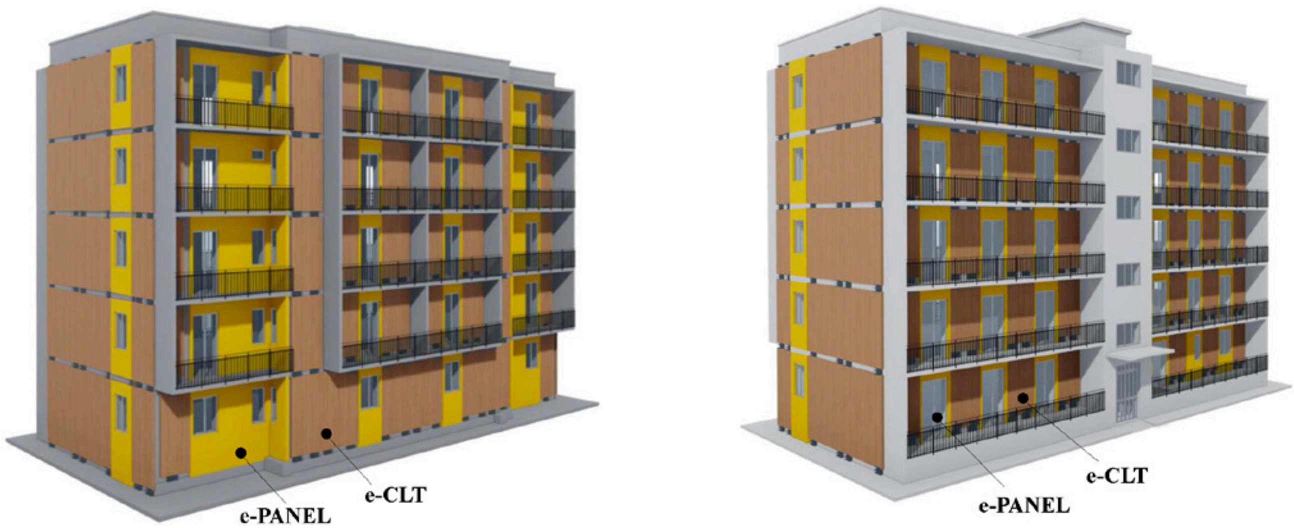
Based on the above construction analysis, potential application solutions of the proposed retrofit technology are illustrated in Section 4 to investigate its technical feasibility and versatility.

4. APPLICATION SOLUTIONS

Figure 7 schematically shows an example of the application of the proposed technology to a case study.

The case study is an RC framed apartment block (Fig. 7a) built in 1964 and located in the city of Catania (Sicily, Southern Italy). It belongs to a public housing compound and is representative of the buildings erected in Southern Italy before the issue of the most recent and restrictive national regulations on seismic resistance and energy efficiency in buildings. Indeed, the RC framed structure is mainly arranged along the longitudinal direction, while the external infill walls are made of two leaves of hollow concrete light blocks (8-cm thick internal leaf and 12-cm thick external one), with an intermediate non-ventilated, non-insulated air cavity (9-cm thick).

(a)



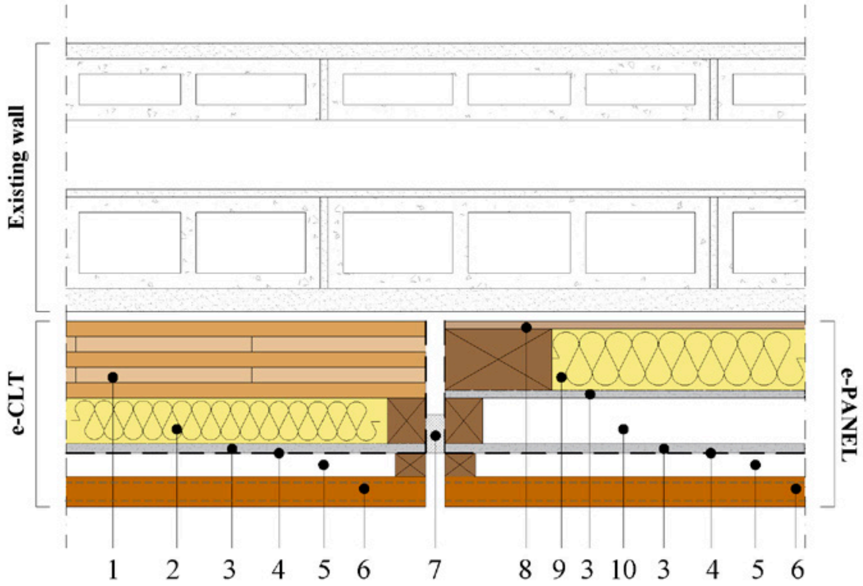
(b)

Fig. 7. *Pilot building in its current state (a); application of e-PANELs and e-CLTs to the pilot building (b).*

In the post-renovation state, the structural e-CLT panels are applied to the outer blind walls of the building by assuming their uniform arrangement on the opposite building fronts, according to the concept of the retrofit technology (Fig. 7b). Conversely, the e-PANELs are applied to all the windowed walls.

Potential application solutions of the proposed technology are here illustrated, with a focus on the main technological issues discussed in Section 3.2. These solutions are aimed at: 1) ensuring the correct operation of the technology in case of dampers' activation; 2) ensuring the high durability and the quality performance of the system; 3) providing a proper architectural integration of each component.

Figure 8 shows an example of stratification for the e-CLT and e-PANEL. The e-CLT is assumed to be made of a 10-cm thick CLT panel coupled with a 6-cm thick wood fibre insulation layer, while the e-PANEL integrates an 8-cm thick wood fibre insulation layer. These stratifications allow reducing the U-value of the existing wall by complying with the limits set by the current regulations for the climate zone B (Catania). Cement-based boards are inserted into both the panels to ensure adequate fire performance, preventing the wood-based insulating material from contributing to the spread of a fire. Moreover, a weatherproof vapour-open membrane protects the main layers of each panel (i.e., insulation materials, CLT panel,



1. CLT panel, 10 cm
2. Wood fibre thermal insulation, 6 cm
3. Cement-based board, 1.25 cm (e-CLT)/ 1-1.25 cm (e-PANEL)
4. Weatherproof vapour-open membrane
5. Ventilated air cavity, 3 cm
6. WPC slats
7. EPDM softband
8. OSB board, 1 cm
9. Wood fibre thermal insulation, 8 cm
10. Non-ventilated air cavity, 6 cm

Fig. 8. *Horizontal section of e-CLT and e-PANEL.*

etc.). A 3-cm thick air cavity is also provided between the insulation and the cladding layers to reduce building thermal loads in summer while also drying rainwater infiltration or winter moisture. Then, a cladding layer made of wood-plastic composite (WPC) slats is assumed for both kinds of panels. According to the above stratifications, the total panel thickness is 24 cm.

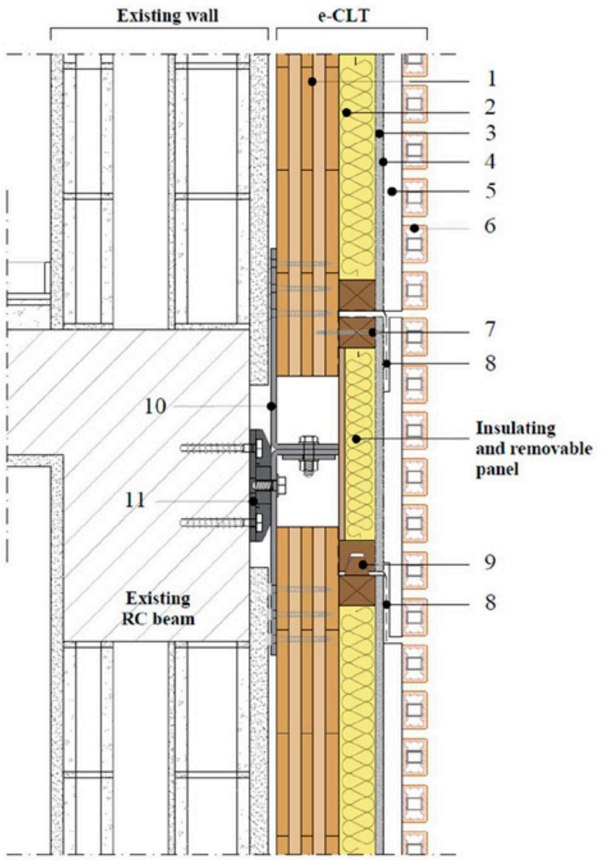
The e-CLT and e-PANEL are not connected to each other, as reported in Section 3.2. Instead, they are separated by a 2.5-cm wide joint that is protected from rainwater infiltration through an UltraViolet (UV)-resistant EPDM softband.

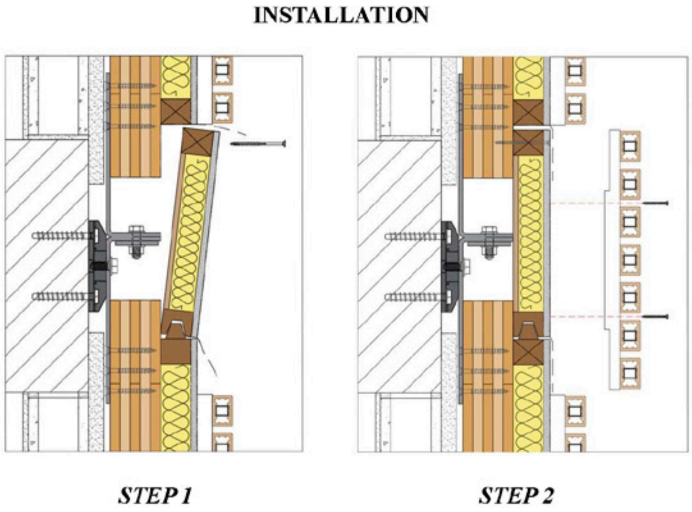
Figure 9 reports potential components to cover the dampers after e-CLT and e-PANEL installation. These components are prefabricated panels that must be removable for dampers inspection and maintenance. They have a wooden frame structure and integrate insulation material. On one side, each panel is fixed to the e-CLT of the upper storey through standard screws, while it is put on the e-CLT of the bottom storey by means of a tongue and groove joint; in this way, it can follow the sliding of the upper e-CLT in case of dampers activation without suffering damage.

The solution in Figure 9a provides for the installation of the cover panel in multiple steps, which include: 1) installing the cover panel and overlapping its weatherproof membrane to one of the upper and bottom e-CLTs to protect the joints from water infiltration; 2) fixing the cladding substructure (e.g., aluminium or wooden studs) and then the cladding layer. This solution is suitable for various cladding materials. For instance, porcelain stoneware tiles can be fixed and removed through standard clip systems, while pre-plastered cement boards or wooden staves through pre-painted screws.

On the other hand, the solution in Figure 9b provides for the total prefabrication of the panel, which also integrates the cladding layer off-site. In this case, the panel is screwed to the upper e-CLT using an aluminium plate that is pre-fixed to it. Aluminium flashings are also provided on its upper and lower side to avoid water infiltration since the overlapping of the weatherproof membranes cannot be achieved in this case.

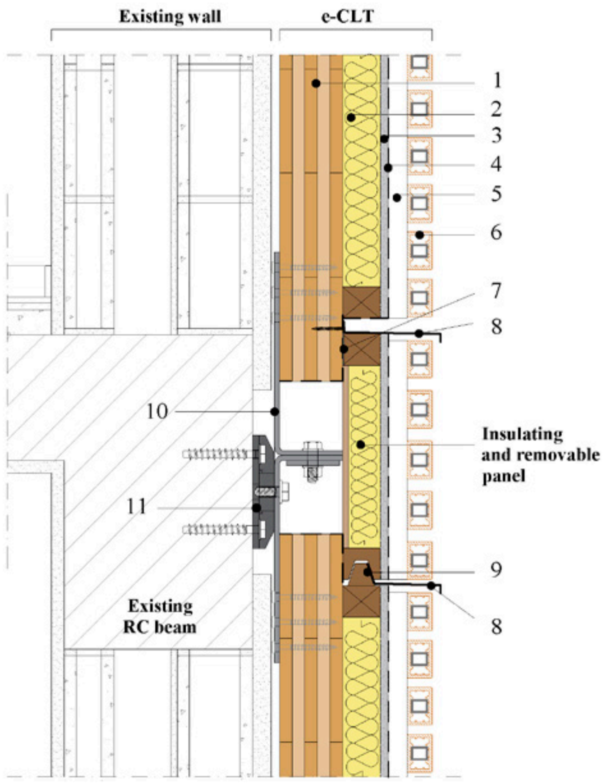
The above-described insulating and removable cover panel is also used to connect two consecutive e-PANELs, thus ensuring an architectural uniformity of the entire façade.





1. CLT panel, 10 cm
2. Wood fiber thermal insulation, 6 cm
3. Cement-based board, 1,25 cm
4. Weatherproof vapour-open membrane
5. Ventilated air cavity, 3 cm
6. WPC slats
7. Screw connection to the e-CLT of the upper storey
8. Overlapping of the weatherproof membranes
9. Tongue and groove joint
10. Friction damper
11. Fixing plate

(a)



1. CLT panel, 10 cm
2. Wood fiber thermal insulation, 6 cm
3. Cement-based board, 1,25 cm
4. Weatherproof vapour-open membrane
5. Ventilated air cavity, 3 cm
6. WPC slats
7. Aluminium plate pre-fixed to the panel and to be fixed to the e-CLT of the upper storey
8. Aluminium flashing
9. Tongue and groove joint
10. Friction damper
11. Fixing plate

(b)

Fig. 9. *Cladding solutions to cover the dampers after the e-CLTs installation: (a) partially prefabricated cover and (b) totally prefabricated cover.*

5. POTENTIALITIES AND APPLICATION LIMITS OF THE PROPOSED RETROFIT TECHNOLOGY

The main target of the proposed retrofit technology is multistorey residential RC framed buildings built between the 1950s and the 1990s. These buildings usually have regular openings on façades, which allows for uniformly applying the structural e-CLT panels to each building storey. Specifically, the system can be effectively used in buildings provided with outer blind walls where an adequate number of structural panels should be applied to ensure the expected level of seismic upgrading.

Detached buildings are better suitable for this technology since the e-CLTs can be added to each front of the building. Otherwise, the internal application of the e-CLTs to the walls between two buildings might be required.

If there are colonnades at the ground story of the building, the e-CLT panels will need to be applied to them. This will be possible if the CLT application does not affect the use of these areas.

Many garages or commercial premises with many large shop windows may also preclude the e-CLTs application, unless the surface of the windows is reduced during the renovation works. Even an extensive use of bow-windows limits the application of the structural panels, which cannot be connected directly to the beams of the RC structure, thus considerably reducing the effectiveness of this solution.

Figure 10 shows some examples of buildings suitable to be renovated with the proposed retrofit technology.

The above analysis of the main target buildings is at a preliminary stage. More investigations are required based on the developments of the technology.

6. CONCLUSIONS

This paper describes and analyses the technical feasibility and versatility of a novel technology for the integrated seismic and energy renovation of RC framed buildings. The proposed technology consists of applying prefabricated, insulating timber-based panels to the existing outer walls of the building by combining structural CLT-based panels equipped with innovative friction dampers with non-structural wooden-framed panels hosting high-performing windows. The result is a new prefabricated shell that acts as seismic-resistant and energy-efficient skin, also contributing to renovating the architectural image of the building.

Specifically, this work analyses the main technological issues of the proposed intervention and investigates technical solutions to ensure a correct operation during seismic events, a high durability and quality performance of the main components, as well as a proper architectural integration. The investigated solutions, applied to a case study located in Southern Italy, show the effective applicability of this retrofit technology to the main target buildings (multistorey residential RC framed buildings built between the 1950s and the 1990s) and ensure a high level of prefabrication, thus significantly reduce implementation costs and time and occupants' disruption. Moreover, the proposed intervention turns out to be highly versatile since it does not require too much space

Fig. 10. *Examples of target buildings located in Catania (Southern Italy, high seismic zone).*

around the building, thanks to the limited thickness of the panels.

Further technical investigations will be conducted according to the results of the ongoing multidisciplinary research that is involved in developing the proposed retrofit technology.

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Authors contribution

Conceptualization, G.M. and C.T.; writing – original draft, C.T.; writing – review and editing, G.M. and C.T.

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