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Application of CLT prefabricated exoskeleton for an integrated renovation of existing buildings and continuous structural monitoring

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Abstract

To reach the ambitious target of decarbonization by 2050, a deep transformation of the construction sector and a systematic renovation of the existing building stock, is required. To be effective, such a renovation requires the adoption of a Life Cycle Thinking (LCT) approach and the implementation of new digital tools to maximize the performances, while enabling the reduction of impacts and costs along the whole building life cycle. The paper proposes a retrofitting intervention, applied to a real case study, that accounts for all these aspects and it is conceived to be applied from the outside, without relocating the inhabitants as to overcome one of the major renovation barriers. From a structural point of view, the retrofit solution entails the adoption of a wooden shell made of CLT prefabricated panels, connected to the building and to the foundations by means of dry, standardized and easy demountable connections, also lumping damage in case of earthquakes. For improving the energy efficiency an optimized thermal layer is applied on the envelope, and a new plant system is introduced around the structural shell. The new plant system enables inspectability and the possibility of further implementation of components over time without interrupting the building functions. Finally, additional sensors are adopted for the continuous monitoring of structural health, energy consumption and comfort relevant metrics.

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1. Introduction

The construction sector is one of the most impacting in terms of greenhouse gas emissions, energy consumption, raw material depletion, and waste production (JRC 2014). A great effort is thus required for this industry to become more sustainable and to proactively contribute to the European goal of carbon neutrality by 2050. In this transition, the deep renovation of the existing building stock is also critical, as highlighted by the recent European 'renovation wave' roadmap (COM 2020) and by the 'New European Bauhaus', since existing buildings are expected to constitute about 85% of the 2050 European construction heritage (BPIE 2020).

In this scenario, it may be observed that the effort to build a few new sustainable green buildings or to renovate buildings targeting the sole energy efficiency is totally insufficient. To reach the ambitious EU goals, a complete transformation of the construction industry and of the concept of building renovation inspired by the Life Cycle Thinking (LCT) approach is required (Huang et al. 2020, Passoni et al. 2021). When the time frame is extended to the whole building life cycle, different building needs should be considered and additional impacts mitigated. For example, at the product stage, impacts due to material supply and production should be minimized; at the construction stage, impacts connected to the transport and to the construction process should be limited; in the use stage, the energy consumption should be minimized together with impacts connected to maintenance, to the possible change of destination use, or, even more importantly, to possible hazards such as earthquakes or superstorms; finally, impacts connected to demolition/deconstruction of buildings and to waste management should be addressed since the earlier steps of the design phases. When the LCT approach is considered during the selection of a retrofit strategy, new LCT design principle, such as prefabrication, standardization, off-site production, adoption of eco-efficient materials, etc., may be defined and adopted to conceive and design new sustainable retrofit techniques (Passoni et al. 2022). In addition, IT and digital tools must be adopted to increase the efficiency and the sustainability of both the construction supply chain and the retrofitted building.

In this paper, a technology enabling the renovation of the existing buildings under a structural, energy, architectural, and functional point of view is proposed. The solution is a layered wooden construction technology, which implements many LCT principles and includes digital tools for home automation and structural health monitoring. The solution, developed within an industrial project integrating academic research and industrial leading-edge technologies, is first described and then applied with reference to an existing post World War II masonry building adhibited to social housing.

1.1. Holistic retrofit of existing buildings: a layered multi-functional exoskeleton

The solution, proposed for the retrofit of existing reinforced concrete (RC) and of masonry buildings of no historical value, is a layered multi-functional exoskeleton. Exoskeletons were recently introduced for the holistic retrofit of buildings, and their use quickly spread as they do not require the relocation of the inhabitants (Marini et al. 2017), which is one of the major barriers to renovation (BPIE 2011). Under a structural point of view, exoskeletons may be conceived as a shear wall lateral force resisting system (LFRS), which require the addition of a few seismic resistant shear walls along the building perimeter, or as a shell LFRS, which instead consists in an additional seismic resistant involucre applied to the existing façade (Passoni et al. 2020). The solution proposed in this paper belongs to the latter category and consists in a Cross Laminated Timber (CLT) engineered shell improving the seismic performance of the existing building (Fig. 1). In order to upgrade the energy performance of the building, associated with the façade heat loss, an optimized thermal layer is also added to the façade. Finally, architectural and functional restyling are achieved through tailor-made finishes and plug-in modules to be applied to the structural shell, introducing technical or additional living spaces, if needed.

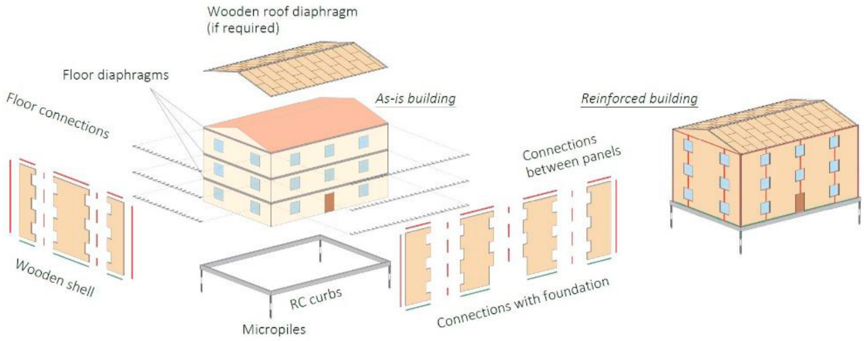

Fig. 1. Wooden exoskeletons for the holistic renovation of existing buildings: possible layout of the structural layer.

This exoskeleton solution is conceived to be compliant with many of the LCT principles (Passoni et al. 2022). is the solution is entirely prefabricated, the main components are made of timber, which is a renewable bio-based materials, and it is connected to the building and the foundations by means of dry, standardized and easy demountable connections, enabling concentrating damage in case of earthquakes. Off-site prefabrication of components optimizes the use of material, reduce variations, and speed up construction, resulting in a greener, safer and cleaner construction site; whilst the adoption of the standardized connections minimizes impacts at the end of life of the building, allowing easy selective dismantling of the exoskeleton and the reuse of the components.

This solution, the 'AdESA system' (whose acronym stands, in Italian, for: Adeguamento Energetico Sismico Architettonico, Energy-Seismic and architectural retrofit), was first introduced in 2017 (Report AdESA 2019), then successfully applied to an Italian school gym (2019-2020), and finally published in Zanni et al. (2021). In this paper, the system is further engineered, introducing a new type of connections between the structural layer and the foundation, which allows easy dismantling and reusability of the CLT panels. In addition, a new plant system substituting the existing plants without interrupting the building functions is introduced along each external floor perimeter. Finally, a supplemental "implementable" home automation system, enabling flexibility of the building use, and additional sensors for the continuous monitoring of structural health, energy consumption and comfort relevant metrics are introduced.

1.2. A novel plant system and home automation ensuring flexibility and adaptability

The proposed technology implements an innovative, efficient, patented distributed system developed to substitute traditional wall and in-wall water supply pipes and electric wiring with a new type of pre-assembled isolated pipes, called Fluxus Ring® (Fig. 2). In this system, pipes are placed in a wall-mounted aluminum housing on the outer façade of the building, thus not requiring inhabitants' relocation, are easily inspectable, thus facilitating maintenance activities, and only need to be connected to the existing radiators (whose substitution may be optional, unless mandatory duo to possible obsolescence), as their installation does not require any masonry work. The pipes' ample aluminum housing also serves as a multi-service physical infrastructure allowing integrations and implementations of hydraulic, electric, multimedia and building & automation control systems (BACS), as well as optic fiber.

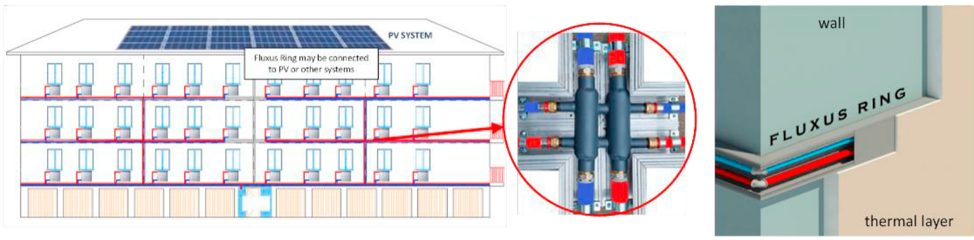

Fig. 2. Additional plant system along the outer building perimeter in correspondence of the floors (Fluxus-Ring®, ©ItaliaSmartBuilding).

1.3. IT for continuous monitoring of key performances

The additional exoskeleton implements sensors for the monitoring of relevant key performances of the building, such as energy consumption, comfort of the inhabitants, and structural health of the building. In particular, Structural Health Monitoring (SHM) is a typical damage detection process of aerospace, civil or mechanical infrastructures. This process involves the observation of the structure over time, the extraction of figures from relevant measures sensitive to structural damage, and, finally, the statistical analysis for the automatic detection of the state of health. For permanent or long-term SHM, the process allows periodic updating of the collected information, being able to detect the progress of the damage, physiological in all structures, such as the inevitable degradation due to corrosion in metal-based materials. In the case of an extreme event, such as an earthquake or an explosion, the SHM could be useful for the quick screening and assessment of the post-event structural conditions in almost real-time. In the upgraded version of the AdESA system, data from heterogeneous sensors are processed in parallel to obtain an increasingly complete and accurate description of the structural health.

2. Application to a case study building

2.1. Case study building and performances in the as-is situation

The proposed retrofit solution was applied to a social housing building constructed in 1960, located in Brescia province, in northern Italy. The building has two floors above-ground, each featuring two apartments, and an attic with roofing on staggered levels having a practicable part, used for storage and cellars, and a non-walkable part under the lower pitch.

The plan organization is regular, with a gross surface of about 131 m^2. The main façade has an extension of 13.6 m, the rear façade has an extension of 12.4 m, and the side façades have an extension of 10 m and an indentation of about 0.60 m in the middle of the length (Fig. 3).

The load-bearing structure presents masonry walls made of clay hollow blocks (245x245x120) mm^3, with the holes arranged horizontally, and cement based mortar. In the corners between orthogonal walls and at the ends of longitudinal walls the masonry is made of solid brick; while the walls of the crawl space between the foundations and the first-floor slab are made of solid brick and cement mortar. The floor slabs consist of 0.20 m-high RC beam and clay block system, with spans of 4.20 and 5.00 m, with perimeter RC curbs above the masonry walls and the lowered central beams with a height of about 0.43 m and a span of 4.00 m. The two-roof pitches arranged at different heights consists of reinforced brick joists and hollow-core lacking the extrados screed.

Under a structural point of view, the main vulnerability of the building is represented by the local out-of-plane collapse mechanisms of the masonry on the attic floor, associated with a LSLS safety index of 0.12, due to the absence of a rigid roof diaphragm and the presence of pitches at different levels. The seismic retrofit is therefore necessary.

A finite element model was then assembled to evaluate the global behavior of the building, in the hypoteses the local mechanisms were inhibited. Such an analysis is preliminary to the conceptual design of the global retrofit intervention. The equivalent frame modeling technique was addressed. The non-linear static analyses showed that, upon inhibiting the local mechanisms, the overall vulnerability of the structure is associated with the failure of the masonry walls and the activation of a weak plane mechanism at the first floor, with a LSLS safety index of 0.62.

Moving to the energy considerations, the selected building represents the classical social housing typical of the ’60 and was not improved during the years. The envelope obsolescence is the cause of a poor energy performance, as quite usual of buildings of those years. The walls are covered with plaster and the roof with tiles; all the surfaces lack thermal insulation, and different types of cold bridges can thus be identified. Single glass windows with old frames affect the energy performance and drive a high air infiltration ratio. In addition, the stairwell, which is centrally placed to the main facade, is open to the outer courtyard. The combination of these factors leads to a large energy consumption for space heating and a low indoor comfort for the users.

Finally, under an architectural point of view, the building presented poor conditions and a bad state of preservation with widespread deterioration on the façades and low living comfort for the inhabitants, needing renovation both under an aesthetic and a functional point of view.

Fig. 3. Case study building: view of the main façade and floor plan.

2.2. Design of the exoskeleton performances after the retrofit

In order to contextually solve the structural, energy and architectural deficiencies of the building, a shell exoskeleton consisting of an inner structural layer made of CLT panels improving seismic performance, a thermal insulation layer increasing energy performance and an external finishing layer to improve the aesthetic of the building were adopted. A new plant distribution system, anchored to the structural shell and inspectable directly from the façades was also introduced.

Structural retrofit and performances. The exoskeleton is designed to provide rigid and over-resistant behavior for medium earthquakes, while for higher earthquakes, energy dissipation is lumped in the connections between the CLT panels, thereby avoiding damage in wooden elements and in the connections to foundation. The target of the intervention is to ensure a very small drift at LSLS in the existing masonry walls (<0.4%) so that the load-bearing capacity against vertical loads is not compromised following a medium-to-high intensity earthquake.

The structural exoskeleton is composed of a new foundation system, a wooden shell made of CLT panels and an extrados roof diaphragms with plywood panels.

The foundation system consists of a RC perimetral curb placed in adherence to the existing foundation to support the CLT panels and transfer their actions to small-diameter piles deeply driven into the ground (15 m) to support the tensile and compressive actions induced by the wooden shell, and an outer RC diaphragm (100x20)cm^2 to collect the seismic load of the entire building and ensure its shear-slip resistance with respect to the ground.

The wooden shell is made of 10cm-thick five layers CLT panels, shaped to contour the existing openings. The panels are joined with dissipative connections exhibiting hysteretic behavior ("slices" or segments of HEA100 welded along the flanges, Fig. 4, left), whose ductility was tested through an experimental campaign conducted by University of Bergamo. CLT panels are then connected to the building floors by means of dowels (Φ20/30) and tie rods (Φ12 2/panel) grouted in the RC curbs. The panels are restrained to the new foundation by means of steel ties (Dywidag 18WR), prepared and pre-installed off-site inside the panel and jointed in place with coupler, and shear keys inserted at the base of the panels (Φ50 tubular studs, of 3 mm thickness, welded to the base plate nailed to the panel, Fig. 4, right).

The roof diaphragms, built at the extrados of the two pitches of the existing roof, consist of 3-cm-thick plywood panels joined together with nailed strips and perimeter chords made of steel plates connected to the existing RC curbs by dowels and tie rods and to the CLT walls by nails (Fig. 5 right).

Fig. 4. Pictures of the dissipative connection between CLT panels (left) and between panels and foundation (right) during the assembly phase.

Fig. 5. Picture of the main façade clad with CLT panels during construction stage (left) and picture of the roof diaphragm (right) during the construction phase.

To evaluate the effectiveness of the intervention, a finite element model of the building was implemented with the new exoskeleton, and nonlinear static analysis were carried out. The results show that, with the introduction of the exoskeleton, the structure gains stiffness and strength, and the displacement demand at LSLS is lower than capacity. At this point, plasticization of some dissipative connections is reached while the connections between panels and foundation are all found to remain in the elastic range; internal stresses in CLT panels are lower than the prescribed limits. In the existing structure some masonry walls reach the plasticization; however, the maximum drift recorded is 0.12%, lower than the maximum imposed limit of 0.40% (Fig. 6).

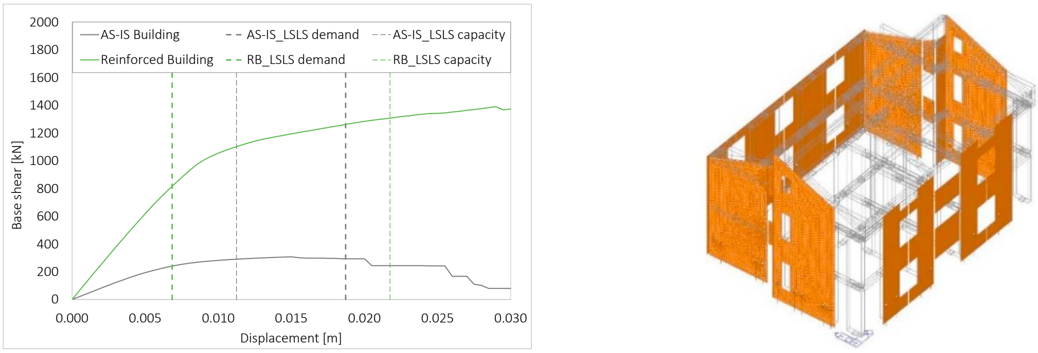

Fig. 6. Comparison between the pushover curve of the As-is building and retrofitted building for X direction (left). Finite element model of the shell exoskeleton (right).

Energy retrofit and performances. As for the energy efficiency enhancement, the intervention is designed to reduce the primary energy consumption and to achieve a higher level of internal comfort.

Coupling the structural layer with an energy layer as shown in Fig. 7, left, allows to reduce the thermal transmittance of the opaque elements and reduce/avoid thermal bridges. Low energy windows installation completes the envelope improvements, whilst the energy system is improved by adopting a new distribution solution without replacing the boiler and the radiators.

The thermal insulation layer is optimized by also accounting for the wooden exoskeleton thermal properties (balancing insulation and thermal inertia).

In order to evaluate the energy performance of the building, and optimize the solution, a detailed transient analysis has been carried out adopting a numerical Trnsys® simulation. Starting from a 3D geometrical model, the analysis considers the behavior of the building including the physical properties of walls and the internal gains (occupancy, appliances, and lights) on hourly basis in terms of temporal and spatial distribution.

To assess the effectiveness of the retrofit, the energy performance of the retrofitted building was compared with that of the building in the as-is conditions in terms of primary energy requirement for the space heating in Fig. 7 (right). The graph shows the monthly heating load and the expected energy savings. The trend presents a wide reduction of the primary energy requirement especially for the cold months. The forecasted peak load shifts from 22 kW to 9 kW whilst, on annual basis, the heating load drops from 54 MWh to 15 MW, with an energy savings of 72%.

Fig. 7. Model of the structural and of the energy layers (left). Comparison between the energy performances of the building in the as-is and retrofitted conditions (right)

Architectural and formal retrofit. Considering the reference building, different architectural solutions were studied. Finally, because of budget restrictions, the façade was finished with a colored plaster, the windows were substituted, and the staircase core was closed so as to improve the energy performance of the building and increase the comfort of the inhabitants.

Additional plants. The exoskeleton was equipped with the Fluxus Ring® system, in correspondence of each floor (according to Fig. 2). This would enable possible future modification of the plants by operating from the outside, without interrupting the building functions, thereby meeting the requirements of building flexibility and adaptability.

This objective can be achieved thanks to the flexibility of Fluxus Ring®, which allows the plants in the building to be modified/integrated/replaced according to the evolving needs of its occupants, in line with the LCT approach and the principles of the incremental rehabilitation.

IT for the continuous monitoring. In this work, a multi-purpose monitoring infrastructure was developed, including wood moisture sensors for CLT and plywood panels, accelerometers for the acquisition of vibrations and earthquakes, and a weather station for the detection of environmental parameters such as humidity, temperature, pressure and wind speed.

The infrastructure has two processing layers. First, the data is processed and stored locally, and then it is synthesized and sent in the cloud to the *Big Data platform*. The implemented algorithms have different degrees of refinement, with the sole objective of identifying the state of health of the building; one shifts from simple moving averages, up to integrations of accelerometric signals over time, and evaluation of the degree of damage induced by an earthquake. Finally, the *Big Data platform* enables to visualize the transmitted data and to impose technically effective thresholds to detect any possible deviations from the acceptable performance.

3. Concluding remarks

The ambitious target of decarbonization requires a deep change of the current practices adopted in the construction sector. In the present paper, a new technology inspired by the principles of Life Cycle Thinking and integrated with innovative digital tools is proposed for the holistic and smart renovation of the existing building stock, which is widely acknowledged as responsible of great impacts. The solution consists in a prefabricated multi-layered timber exoskeleton, implementing bio-based materials, standardized elements, and dry and demountable connections. An innovative system to introduce new plants without relocating inhabitants is provided, and sensors are installed to guarantee comfort of the inhabitants, optimization of energy consumption, and monitoring of the structural health of the building.

The presented solution, which results from the collaboration of academic and industrial partners, represents the evolution of the prototype AdESA system, which is here further enhanced by enforcing the application of the LCT principles and by implementing digital technologies to improve building performances and comfort of the inhabitants. The presented application is under development. Observations from this pilot application will enable further enhancement of the proposed technology and will improve the replicability of the solution.

References

JRC Report EUR 26497 EN, Marini, A., Passoni, C., Riva, P., Negro, P., Romano, E., et al. (2014). Technology options for earthquake resistant, eco-efficient buildings in Europe: Research needs, Report EUR 26497 EN. JRC87425.

COM (2020) 662 final. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Brussels, 14.10.2020.

BPIE Report (2020). Vitali Roscini A., Rapf O., Kockat J. On the way to a climate-neutral europe. Contributions from the building sector to a strengthened 2030 climate target.

Huang B., Gao X., Xu X., Song J., Geng Y., Sarkis J., Fishman T., Kua H., and Nakatani J. (2020). A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials, One Earth, 3, pp. 564-573, November 20, 2020.

Passoni C., Marini A., Belleri A., Menna C. (2021). “Redefining the concept of sustainable renovation of buildings: state of the art and an LCT-based design framework.” Sustainable Cities and Society, 64, January 2021

Passoni C., Palumbo E., Pinho R., Marini A. (2022). "The LCT challenge: shifting the mindset to foster sustainability of building retrofit interventions". Submitted to: Sustainabilty

Marini A., Passoni C., Belleri A., Feroldi F., Preti M., Metelli G., Giuriani E., Riva P., Plizzari G. (2017): “Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept.” European Journal of Environmental and Civil Engineering.

BPIE Report. (2011). Europe’s buildings under the microscope: A country-by-country review of the energy performance of the buildings, Brussel, October 2011.

Passoni C., Guo J., Christopoulos C., Marini A., Riva P. (2020) “Design of dissipative and elastic high-strength exoskeleton solutions for sustainable seismic upgrades of existing RC buildings.” Engineering Structures, Volume 221, 15 October 2020

AdESA (Adeguamento Energetico Sismico ed Architettonico). Final Report. Project ID n. 379259; Smart Living Project; Regione Lombardia: Brescia, Italy, 2019

Zanni J., Cademartori S., Marini A., Belleri A., Passoni C., Giuriani E., Riva P., Angi B., Franchini G., Brumana G. (2021). Integrated Deep Renovation of Existing Buildings with Prefabricated Shell Exoskeleton: The AdESA Case Study. Sustainability, 13, 11287