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APPLICATION OF A WOODEN PREFABRICATED SHELL EXOSKELETON FOR THE INTEGRATED AND SUSTAINABLE RETROFIT OF A RESIDENTIAL BUILDING

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ABSTRACT: The ambitious target of decarbonization requires a deep transformation of the construction sector and a systematic renovation of the existing building stock. Such a transition requires the adoption of new technologies conceived with a Life Cycle Thinking approach and implementing digital tools, maximizing performances, while enabling reduction of impacts and costs along the building life cycle. In the paper, a wooden construction technology for the deep renovation of existing buildings is presented. The solution is prefabricated off-site, made of a renewable bio-based material, and adopts innovative dry, standardized connections, enabling concentrating damage in case of earthquakes. The system is applied from the outside, without relocating inhabitants, that might otherwise hinder the renovation. An additional CLT engineered shell, coupled with an optimized thermal layer and new plants along the building perimeters, allow the combined energy and structural upgrade of the building. Finally, specific sensors are added for the continuous monitoring of structural health and environmental parameters. The proposed solution was developed within an industrial project integrating academic research and industrial leading-edge technologies and was applied to a typical post-WWII masonry building.

KEYWORDS: Wooden exoskeleton, Cross-Laminated Timber (CLT), Life Cycle Thinking (LCT), Holistic renovation.

1 INTRODUCTION

A great effort is required to the construction sector to become more sustainable and to proactively contribute to the European goal of carbon neutrality by 2050 [1]. In this transition, the deep renovation of the existing building stock is critical, as highlighted by the recent European “renovation wave” roadmap [2] and by the “New European Bauhaus”, since existing buildings are expected to constitute about 85% of the 2050 European construction heritage [3].

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 [4,5]. Adopting a LCT approach in the building renovation process means considering the fulfillment of the building needs and the reduction of potential impacts along its whole life cycle, from renovation to end of life. 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, the role of structural engineers become critical in the definition and the detailing of the techniques. Life Cycle Structural Engineering (LCSE) should thus be adopted, including new LCT design principles, such as prefabrication, standardization, off-site production, adoption of eco-efficient materials, etc., to conceive and design truly sustainable retrofit techniques [6].

Economic sustainability of the interventions should also be considered when a LCT approach is pursuit. To overcome the economic and operational barriers that arise

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for the rehabilitation of buildings in case of restricted budgets, the incremental rehabilitation approach may thus be adopted. This concept, introduced in [7] and further explored in [8], among others, involves planning a comprehensive intervention through a series of steps distributed over time and organized according to structural (minimum intervention), economic (budget limitations) and functional criteria (site sharing with planned maintenance interventions) so as to ensure the feasibility and effectiveness of the intervention.
From these premises comes the idea of employing holistic renovation techniques built from the outside of the building, coupling seismic reinforcement exoskeletons with energy and plant efficiency systems and with customizable architectural finishes, designed to meet the LCT principles and to be realized according to an incremental rehabilitation perspective [9].
Among these solutions, some of the authors recently proposed the AdESA System [10, 11], a wooden shell exoskeleton composed of a structural, energy, and architectural layer, able not just to guarantee maximum structural, energy and comfort performances, but also to minimize environmental, social, and economic impacts along the retrofitted building's life cycle, being conceived including some LCT principles such as material eco-efficiency, prefabrication, standardization, damage control, demountability, and reusability, among others. In this context, the use of wood-based materials allows, on the one hand, to limit the environmental impacts thanks to the use of a material with a positive CO_2 emission rate, and, on the other hand, to take advantage of the great potential offered by wood in structural and technological terms, such as prefabrication, standardization of connections, speed of assembly, ease of work on site and integration with insulation and finishing systems.
With respect to the first concept of the AdESA project, this paper presents an advancement of the solution. The system was here further engineered by improving the foundation connection system to enhance the demountability of the structural system, by introducing new plants from the outside, and by introducing a continuous monitoring of performances to ensure the building safety, efficiency and durability. The paper present the application of the enhanced system to a real case study, developed within the SCC Innovation Hub & Living Lab Network project (financed by Regione Lombardia, Italy), which, thanks to the collaboration between university and industrial partners involved in the construction and telecommunications sectors, has made it possible to conceive and implement an LCT-based integrated rehabilitation intervention on a social housing residential building featuring an additional prefabricated wooden shell exoskeleton.

2 GLOBAL CONCEPT OF THE INTERVENTION

The goal of the project was to design and apply an LCT-based integrated retrofit intervention to a residential social housing building, in order to achieve better performances and reduce the impacts of the building along its life cycle. The main constraints imposed by the project include adherence to planned budget limits and the need to not interfere with the functionality of the building by ensuring inhabitants full access to living spaces during the renovation works.
The proposed solution, developed from previous studies and applications within an ongoing research project carried out by the University of Bergamo and other partners, involves working from the outside through the implementation of an additional skin (the AdESA system [11]), arranged along the perimeter of the building in adherence to the existing walls, and consisting of three functional layers: structural, energetic and architectural.
The inner layer, which is a structural shell exoskeleton, constitutes a new seismic-resistant system that works in parallel with the building to which it is connected, ensuring an increase in overall strength and stiffness. The thickness of this layer can vary depending on the materials used and the structural solution adopted (e.g. single walls, coupled walls, shell). This is overlaid with the energy layer, made of thermal insulating materials capable of reducing the transmittance of opaque walls by limiting heat loss between inside and outside. A variety of thermal insulating materials are available to reach the same final energy performance. The choice of the best material depends on the transmittance and thermal capacity of the existing walls and of the structural layer selected, on the environmental impacts related to the materials, and on the total allowable thickness for the exoskeleton according to local building codes and functional needs. Finally, the architectural layer encloses the finishing of the new envelope and has both an aesthetic and protective value for the underlying layers. Since this layer does not have to perform energy/structural functions, it is highly customizable and can range from traditional solutions with painted plaster to panelized cladding with a variety of geometric and material textures.
From the LCT perspective, the system is studied to implement dry-mounted elements that, on the one hand, limit the use of raw materials and operations for on-site installation, and, on the other hand, ensure easy disassembly for the purpose of inspecting and maintaining the layers behind as well, and to enhance recyclability and reusability of the elements at the end-of-life stage. In addition, the system is also design to minimize the impacts due to earthquakes.
An important innovation introduced by the SCC Innovation Hub & Living Lab Network project concerns the implementation of a new plant distribution system integrated into the energy layer. The system, called Fluxus Ring®, is developed to substitute traditional wall and in-wall water supply pipes and electric wiring with a new type of pre-assembled isolated pipes, with the aim of making them easy to locate, inspect and implement over time thanks to a removable sheet metal cover and the use of special components that allow new utilities to be moved or added within the building without requiring any masonry work. In addition, another advantage is to create,

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along the perimeter of each floor, equipotential rings that limit energy losses at the various utilities. The system consists of modules made up of extruded aluminum C-shaped profiles and sheet metal covers with a small footprint (103x265 mm) designed as a multi-service physical infrastructure able to accommodate all the plant ductwork expected for a residential building (hydraulic, electric, multimedia and building & automation control systems, optic fiber) (Figure 1).

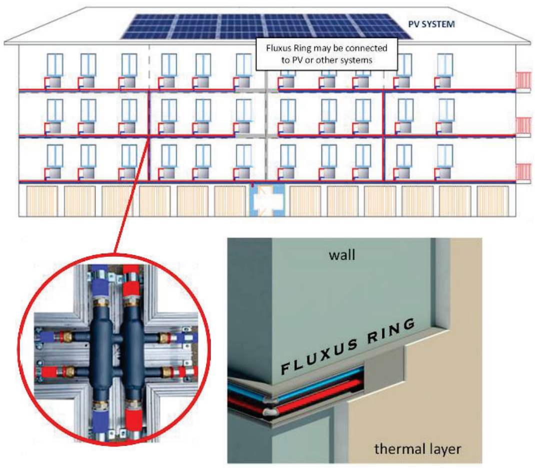

Figure 1: *Fluxus Ring system (©Italia Smart Building)*

In order to guarantee the building performances during its use phase, an aspect of great importance concerns the continuous structural health monitoring (SHM) [12]. This process involves the observation of the structure over time, the extraction of features from measures sensitive to structural damage, and, finally, the statistical analysis for the automatic detection of the state of health.
To this end, SHM systems consisting of tools for acquiring, processing, storing and sharing data on digital platforms were designed (Figure 2). The monitored parameters are the building's vibration frequencies, through the acquisition of accelerations induced by environmental vibrations and seismic events, and the state of preservation of the material constituting the structural exoskeleton, by measuring the moisture content in the CLT panels. These parameters, compared with the targets used in the design and construction phase, can provide important feedback on any damage or deterioration phenomena not directly detectable by visual inspections.

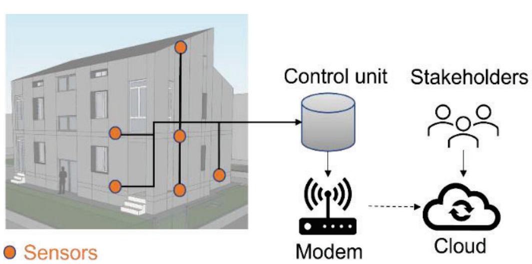

Figure 2: *Structural Health Monitoring concept*

3 DESCRIPTION OF THE REFERENCE BUILDING

In the project, the proposed LCT-based wooden retrofit solution was applied to a residential building. The case study is a social housing building constructed in 1960, located 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 as shown in Figure 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 (75 cm above ground level) are made of solid brick and cement mortar, resting on continuous perimetral foundation made of unreinforced concrete mixed with stones. The floor slabs consist of 20 cm-high RC beam and clay block system, with spans of 4.20 and 5.00 m and perimeter curbs above the masonry walls made of poor quality weakly reinforced concrete.
The two-roof pitches, arranged at different heights, consists of reinforced brick joists and hollow-core lacking the extrados screed.

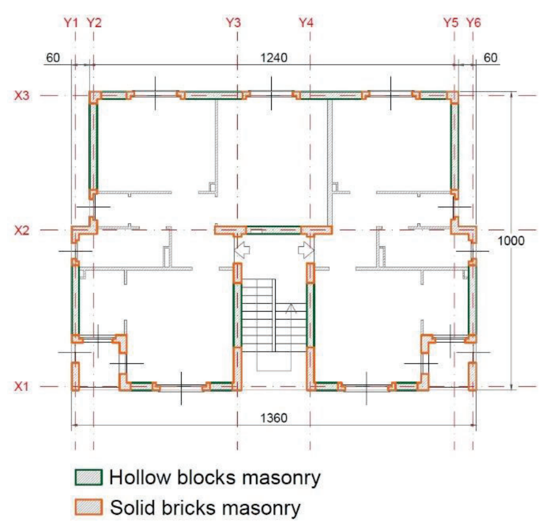

Figure 3: *Floor plan of the building*

Under a structural point of view, masonry walls exhibit vulnerability both with respect to out-of-plane actions, due to the absence of roof diaphragm providing effective constraint against overturning, and with respect to in-plane actions, due to the masonry quality that exhibits

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poor mechanical performances and more brittle behavior than traditional masonry type due to the arrangement of hollow blocks [13]. The reference seismic spectrum at LSLS is obtained, according to Italian code [14], from the following parameters: $a_g = 0.158$ g, $F_0 = 2.463$, $T_c^* = 0.266$ s, S = 1.200. 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 safety index of 0.12. The seismic retrofit is therefore necessary.

Moving to the energy considerations, the selected building represents the classic example of social housing 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 façade, is open to the outer courtyard (Figure 4). The facilities are outdated and inadequate. 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.

Figure 4: *Picture of the main façade*

4 DESIGN OF THE RETROFIT INTERVENTION

4.1 STRUCTURAL LAYER OF THE INTERVENTION

The choice to intervene from the outside to avoid inhabitants' relocation implies the introduction of new seismic-resistant systems that cooperate with those of the existing building, called exoskeletons [15,16]. This requires special attention in the evaluation of the actions transferred at the floor and foundation levels and in the definition of the relevant construction details. Furthermore, to enable the transfer of actions between the exoskeleton and the existing building, preliminary verification and possible reinforcement of the existing floor diaphragms is necessary as they represent indispensable elements of the seismic force resistant system [17,18].

Exoskeletons can be divided into two main categories according to their structural organization: bi-dimensional and three-dimensional systems.

Bi-dimensional (or wall) systems are those applied on individual building façades, designed to make a resistant contribution only in the reference direction without interacting with systems arranged on adjacent façades. Three-dimensional systems (or shell structures), on the other hand, are characterized by the widespread presence of structural elements along all façades that cover the entire exterior surface of the building. This has significant advantages from a structural point of view since orthogonal walls, being connected to each other, make it possible to increase overall stiffness and strength by reducing stress on individual elements and in the foundation.

For the definition of the seismic retrofitting intervention, performance targets that are stricter than those required by the Italian national standard [14] have been identified to respect those LCT principles connected with the damage and downtime minimization. According to such principles, in addition to the fundamental criterion of structural safety, it is also important to ensure building resilience through damage control for high intensity earthquakes so as to minimize the economic and social impacts resulting from a seismic event.

Based on these considerations, the Life Safety Limit State (LSLS) was taken as a reference, and it was imposed that: the exoskeleton must be able to transfer the entire seismic action expected for the building; the structure must experience a maximum limit drift of 0.2%, dictated by the poor masonry quality and the need to preserve its strength against vertical loads; residual drift must be limited so as not to compromise disassembly and repairability of components; a ductile collapse mechanism for the building must be ensured.

According to the previous design objectives, the structural exoskeleton applied to the case study building, represented in Figure 5, is composed of a new foundation system, a wooden shell made of 10cm-thick five layers CLT panels connected each other and with existing floors, and an extrados roof diaphragm made 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 16 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.

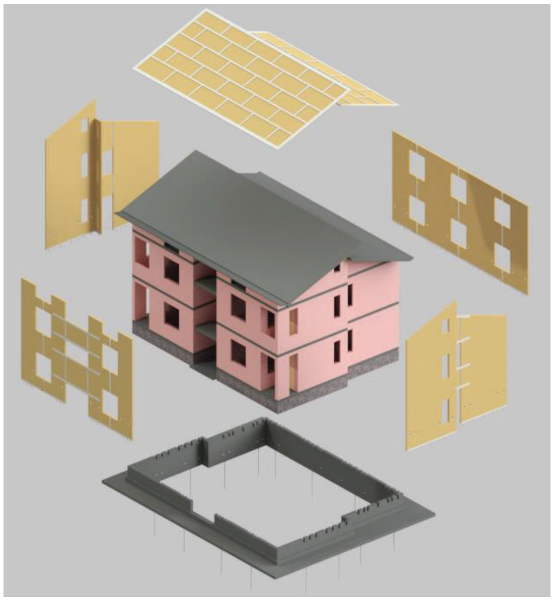

Figure 5: *Layout of the structural intervention*

Given the geometry of the building, the CLT panels are arranged vertically adjacent to the existing wall piers and shaped to contour existing openings (Figure 6). A shear connection is placed between adjacent panels to obtain a coupled wall system with high stiffness, comparable to that of the existing building. The shear connections between panels, shown in Figure 7, were ad-hoc designed to ensure ductile and dissipative behavior by avoiding damage in the CLT panels and keeping the other connections in the elastic range, thus ensuring the minimization of damage and replacement actions in the aftermath of the earthquake. These connections are made with segments of HEA100 welded along the flanges, exhibiting hysteretic behavior due to bending plasticization of web plates, whose ductility was tested through an experimental campaign conducted by University of Bergamo [19]. The connection is prefabricated and mounted to the CLT panels on site by into millings prepared on the edge of the panels and fixed with over-resistant self-drilling dowels.
CLT panels are then connected to the building floors by means of dowels (φ20/30) and tie rods (2φ12/panel) grouted in the RC curbs, designed with elastic and over-resistant behavior.
The continuous connections between adjacent panels and between orthogonal panels were realized by means of cross-connecting screws (φ9x140mm) designed for shear and tensile strength with overstrength behavior.
The panels are restrained to the new foundation by means of unbonded steel ties (Dywidag 18WR) for transferring the high tensile stresses induced by the exoskeleton, 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). The ties are prepared and pre-installed off-site inside the panel and jointed in place with coupler, while the shear keys are housed in special recesses prepared in the cast-in-place foundation curbs (Figure 8) and sealed with high-performance mortar after assembly operations are completed.
The development of this connection system arose from the need to transfer higher shear and tensile actions for which the traditional connections used in new wooden construction (hold-down and angle brackets) are insufficient, but especially to ensure easy assembly and disassembly of the system in the LCT perspective.
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 (Figure 9) 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.

Figure 6: *Prefabricated CLT panels ready to be installed*

Figure 7: *Dissipative connection between CLT panels*

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Figure 8: Panels arranged on the façade and connected with the new foundation

Figure 9: Construction of the diaphragm at the extrados of the existing roof

To evaluate the effectiveness of the structural intervention, two finite element models of the building were developed with Midas Gen and nonlinear static analysis were carried out.
The first model represents the building in the as-is condition in the hypotheses that the local mechanisms were inhibited. Given the regularity and simplicity of the structure, equivalent frame modelling was employed.
The masonry piers were introduced with beam elements with an extension equal to the interstory height, connected by the RC curbs. To both elements were assigned concentrated plastic hinges in shear and bending; in particular, the shear-slip mechanism was evaluated for masonry.
In the second model, shown in Figure 10, the wooden exoskeleton is overlapped to the initial configuration. CLT panels were introduced adopting plate elements and considering the orthotropic properties of the material and the actual geometry and stratigraphy of the adopted panels. Connections were modelled as distributed general links with calibrated stiffness and elastic strength based on the theoretical and experimental behavior of individual connectors. At the base of the panels, compression-only type point spring supports, to simulate the vertical interaction with the reinforced concrete foundation, and rigid shear constraints were introduced.

Figure 10: Finite Element Model of the retrofitted building

The building in the as-is condition develops a soft story mechanism in which capacity is dictated by the achievement of the ultimate flexural drift of the slender wall piers arranged on the main façade. The displacement demand at LSLS is therefore not satisfied.
The results, reported as a comparison of pushover curves in Figure 11, 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, evaluated in accordance with [20] and considering the actual panel stratigraphy, 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 0.20%. The ultimate displacement capacity of the building also increases by moving from a weak storey mechanism to a global mechanism that allows an increase in the ductility of the structure.

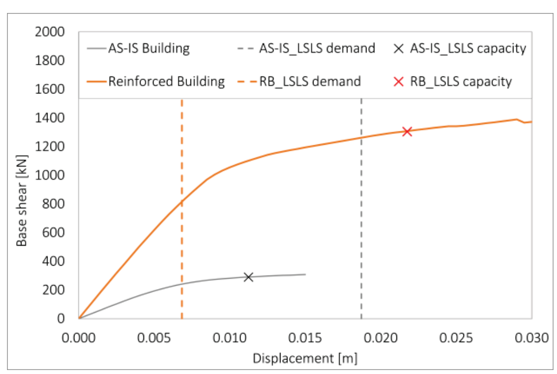

Figure 11: Comparison between the pushover curve of the As-is building and retrofitted building for the main direction

4.2 ENERGY AND ARCHITECTURAL LAYERS OF THE INTERVENTION

The final stratigraphy of the integrated intervention, shown in Figure 12, includes a structural layer with 10-cm-thick CLT panels, covered with an energy layer consisting of 12-cm-thick rock wool panels and completed by a finish with painted plaster. Several proposals were developed for the design of the outer architectural layer to explore the expressive potential of the system, an example is shown in Figure 13; however, the final choice was dictated by the budget constraints.
The energy efficiency intervention also includes closing and insulating the stairwell, insulating the attic floor with 16-cm-thick XPS panels and windows replacement.

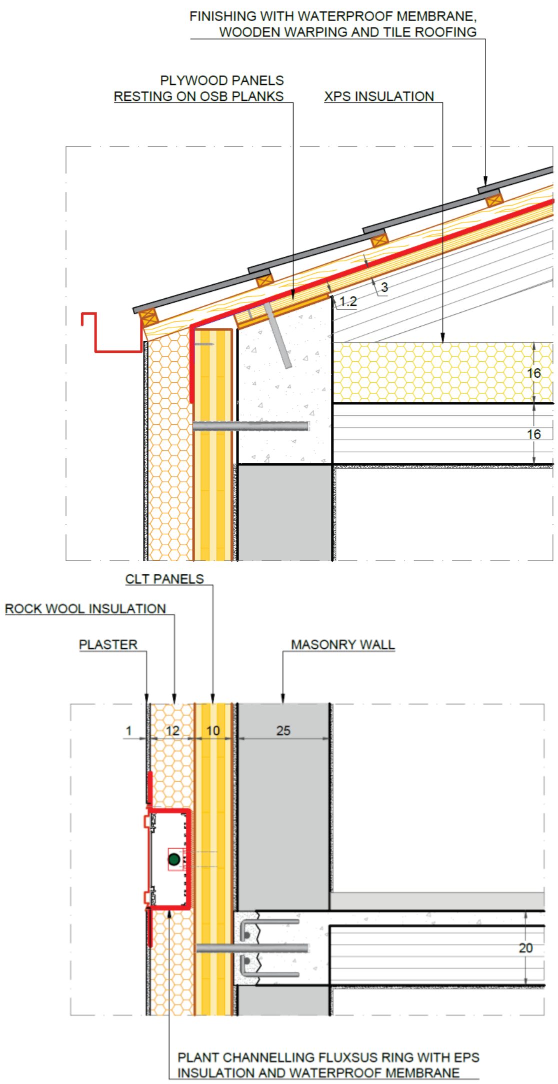

Figure 12: *Stratigraphy of the retrofitted building*

Figure 13: *Rendering of one of the proposed architectural solutions*

From the energy point of view, coupling the structural layer with an energy layer allows to reduce the thermal transmittance of the opaque elements from 0.96 to 0.22 W/(m^{2}K) and avoid cold bridges.
A detailed transient analysis has been carried out adopting a numerical Trnsys simulation. Starting from a 3D geometrical model, the evaluation 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. The results showed a reduction of primary energy requirement for the space heating, compared with the as-is conditions. In fact, as shown in Figure 14, 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%.

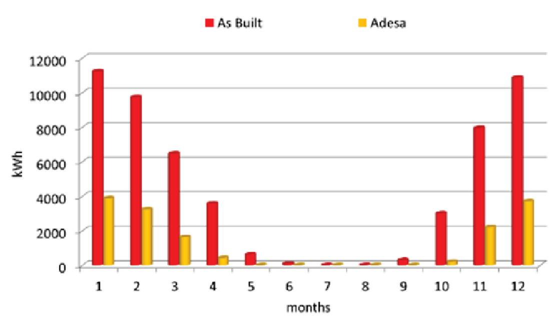

Figure 14: *Comparison between the energy performances of the building in the as-is and retrofitted conditions*

4.3 ADDITIONAL PLANTS FROM THE OUTSIDE AND MONITORING SYSTEM

With respect to the traditional AdESA system, in this project, the integrated renovation solution was further engineered to ensure both the adaptability of the plant system and the monitoring of the building performances along its life cycle. To this aim, the Fluxus Ring ® plant system was installed along the perimeter of the building close to the structural layer, to which it is connected by screws, and, inside it, it was housed the monitoring system (Figure 15) with associated wiring connecting the acquisition instrument to the control unit located in the

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attic of the building where the collected data are processed, stored and shared on a cloud platform.
Eight uniaxial accelerometers, oriented in the three main directions, are placed on the structural layer; two hygrometers are placed on the CLT panels of the north and south façades and one inside the plywood panel of the roof diaphragm. Finally, a weather station is placed on the roof of the building to collect environmental parameters such as humidity, temperature, pressure and wind speed.

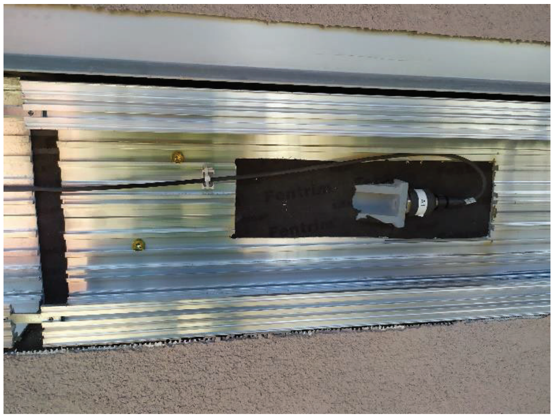

Figure 15: *Placement of an accelerometer within the Fluxus system*

The adoption of Fluxus Ring would allow the substitution and/or future modification of the plants without the relocation of inhabitants, according to the evolving needs of its occupants and in line with the LCT and incremental rehabilitation approaches, thus allowing the building owners to fulfill the requirements of building flexibility and adaptability.

5 CONCLUDING REMARKS

The need to make the building stock more resilient and sustainable requires a deep change of the current practices adopted in the construction sector. In the present paper, a new wooden retrofit technology inspired by the principles of Life Cycle Thinking and Incremental Rehabilitation integrated with innovative digital tools for Structural Health Monitoring is proposed and applied for the holistic and smart renovation of a residential building, which shows important structural, energetic and architectural deficiencies. The solution consists in a prefabricated multi-layered wooden 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 for 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 [11], 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.
In particular, the choice of a material such as wooden panels for the realization of exoskeletons is favorable for intervening on small regular buildings, due to limitations imposed by the mechanical properties of the material and by production and assembly operations. In addition, wooden exoskeletons may be easily conceived to comply with sustainable LCT criteria; timber is in fact an eco-friendly material, produced in certified factories and employed with dry technologies thanks to the use of standardized mechanical connections that reduce site operations. Moreover, wood is easily workable and adaptable on the construction site for the management of interference and assembly tolerances, and it also offers excellent support for the fixing of additional elements such as windowsills, parapets, ventilated façades, technological installations, etc... Also, from the energy point of view, thanks to its thermal properties, timber offers a contribution in terms of insulation, which has positive effects on the thickness of the insulating layer. On the other hand, special attention should be paid to fire and moisture protection of wood in order to ensure durability.
In this paper, the proposed wooden prefabricated shell system was applied for the renovation of a social housing building. The design of the integrated retrofit intervention was discussed, and the enhancement of the seismic and energy performances of the building after the retrofit were shown by means of numerical analyses.
To complete the retrofit intervention, the construction site took 6 months, including 5 months for the structural works; the most time-consuming operations involved the construction of the new foundations, while the installation of 20 vertical CLT panels, with maximum dimension of (250x790x10)cm^3 and the 8 connecting panels took only one week. Figure 16 shows the new building envelope following the completion of the intervention.
Observations from this pilot application will enable further enhancement of the proposed technology and will improve the replicability of the solution.

Figure 16: *Appearance of the building when the work is completed*

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