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COST-PERFORMANCE EVALUATION OF A PRES-LAM CASE-STUDY BUILDING IN ITALY

Giada Formichetti[1], Adriano Francescotti[2], Stefano Pampanin[3]

ABSTRACT: The socio-economic and environmental impacts of recent earthquakes have underscored the need for advanced and sustainable technological solutions in new buildings. The use of engineered timber in construction has gained growing interest in the last years, especially in Italy; nevertheless, it usually comes in the form of conventional platform construction with CLT (Cross-Laminated Timber) walls. Despite the ongoing research to enhance the performance and reduce post-earthquake damage of this system, CLT buildings are often characterized by rigid interior spaces. In contrast, the timber low-damage post-tensioned structural system, known as Pres-Lam, offers large open spaces and high-seismic-performance with negligible damage and recentering characteristics. Although Pres-Lam has been implemented in various countries worldwide, its adoption in Italy is still at early stages. This is primarily due to the lack of awareness and information about the technology, limited familiarity of engineers, architects, quantity surveyors and clients with the use of timber for multi-storey buildings, as well as perceived higher costs when compared to traditional solutions. Through an Academic-Industry research partnership, this paper presents a case-study of a Pres-Lam adaptable building. A real newly designed and constructed CLT platform-type building is re-designed using Pres-Lam technology, and its cost is assessed and compared with the original solution through a comprehensive Bill of Quantities (BoQ). The seismic performance is evaluated through non-linear static analyses, and the environmental impact is assessed by performing a Life-Cycle Assessment (LCA) of the building. The versatility of Pres-Lam is further emphasized by calculating the Building Circularity Score, and by proposing a change in building use from residential to office space throughout its life-span.

KEYWORDS: Post-tensioned timber, Pres-Lam, Low-damage, Adaptability, Costs

1 – INTRODUCTION

As the demand for high-performance, sustainable buildings grows across Europe, timber is becoming an increasingly popular choice in the construction industry. The use of bio-based materials, along with damage-control technologies, might drive the transition towards the Next Generation of buildings, integrating structural performance and energy-environmental aspects to mitigate the significant carbon footprint of constructions [1] also addressing the impact of post-earthquake damage [2]. To this end, the Earthquake Engineering scientific and technical community faces the challenge of establishing higher standards and developing cost-effective, practical design methodologies and advanced technical solutions for future building systems. Developed since 2005 at the University of Canterbury as an extension of the earlier PRESSS system [3], the (unbonded) post-tensioned timber structural system, known as Pres-Lam [4,5] combines low-carbon, dry-jointed modular component with high seismic performance. This technology ensures re-centering capabilities with negligible residual displacements [6] and proper energy dissipation through, respectively, internal unbonded post-tensioned cables/bars and internal or external replaceable (referred to as "Plug&Play") dissipaters [7], developing a peculiar controlled rocking mechanism at the members' interface. Pres-Lam has been successfully implemented in several buildings worldwide, showcasing distinctive architectural features and large open spaces (e.g., [8,9]). Its ease of construction, demountability [10], and

[1] Giada Formichetti, Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome (RM), Italy, giada.formichetti@uniroma1.it, https://orcid.org/0000-0001-7794-5684

[2] Adriano Francescotti, XLAM Dolomiti S.p.A., Via Innsbruck 51, 38121 Trento (TN), Italy, adriano.francescotti@xlamdolomiti.it

[3] Stefano Pampanin, Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome (RM), Italy, stefano.pampanin@uniroma1.it; Adjunct Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

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inherent damage-control properties facilitate the integration of Design for Adaptability (DfA) concept in a broader sense within building design, enabling both functional repurposing and complete reconfiguration of the structure over its (potentially extended) lifespan. However, its adoption in Italy remains at early stages, likely due to industry hesitation towards a new timber system, lack of explicit design code instructions /specifications, and concerns over perceived high costs. With the exception of residential dwellings in the northern (Alpine) regions and Central Apennines, timber itself is still a relatively new material in the Italian construction market, where its recent growth has been primarily driven by the use of traditional platform-type cross-laminated timber (CLT or XLAM [11]) panels [12]. Although recent studies are focusing on innovative connection systems for CLT structures [e.g., 13], their seismic performance inevitably relies on a certain degree of damage to timber. This permanent damage also affects the costs and the sustainability of the construction, which needs to be locally repaired if not disposed and replaced after an earthquake [14]. Moreover, the high number of shear walls resulting from seismic and gravity design - combined with the inherently limited span length capacity of CLT floors - often leads to rigid interior spaces, making harder to accommodate future change in use. This paper explores the benefits of using Pres-Lam for timber buildings through a real case study, thanks to a joint effort between Academia and Industry. By redesigning an existing CLT residential building with Pres-Lam frames and walls, the first-ever, yet partially virtual, cost assessment of a low-damage timber building in Italy is presented through a comprehensive Bill of Quantities (BOQ). Additionally, the building's environmental impact and the integration of circular economy principles are evaluated through Life-Cycle Assessment (LCA) and the Building Circularity Score, respectively. The adaptability of the new Pres-Lam building is further demonstrated by proposing a transformation of the internal architectural layout from residential to office space during the lifespan of the building.

2. PROJECT DESCRIPTION

The Pres-Lam case-study adopted to perform the cost-performance evaluation is based on a real CLT 4-storey building located in Cervia, in the Ravenna province, Emilia Romagna (Fig. 1, left). The lateral load-resisting system (LLRS) comprises all the platform-type CLT shear-walls on the perimeter, as well as those walls separating the apartments at each storey. The flooring system consists of CLT panels as well, and laminated timber or steel beams and columns are used to reduce the floor span length when necessary. A multitude of angle brackets and hold downs are used at the panels-to-foundation and panels-to-floor level connections, and resist the shear and uplift force, respectively. The Gross Floor Area of the building is equal to 2319 m^2, with four balconies at each storey, and an inter-storey height of 3.2 m. Architecturally, the ground floor includes three small apartments and car parking, the first and second floors comprise six apartments, while the third floor accommodates four apartments with additional terraces. The top floor features a pitched roof with timber joists over its central area, and CLT-based stairs and the lift shaft are placed at the core of the building. The same internal architectural layout has been kept for the new Pres-Lam building, shown in Fig. 1 (on the right) and featuring both post-tensioned frames and walls. The Pres-Lam frames represent the LLRS in the shorter direction, made of three spans of 6.7 meters each, while four 2.7 meters-long and 12.8 meters-high Pres-Lam walls has been placed in the longitudinal direction (Fig. 2).

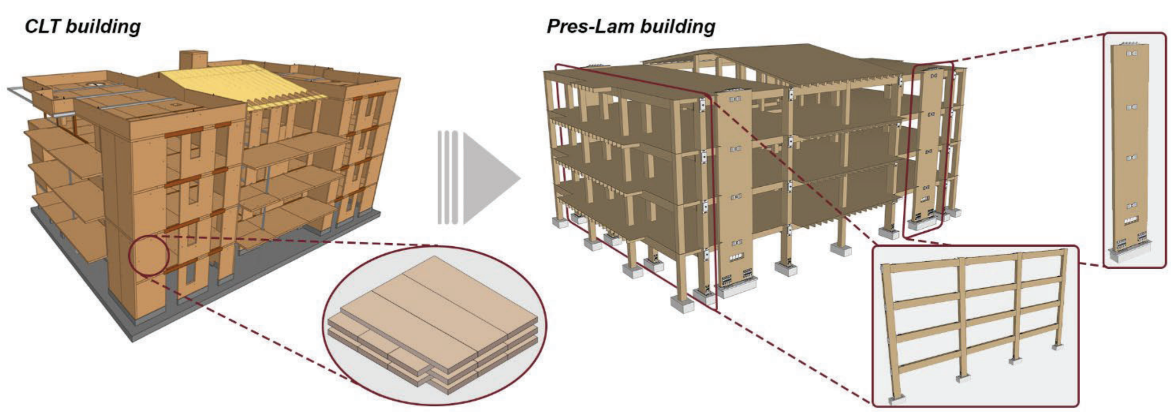

Figure 1. Original CLT building, on the left, and the redesigned Pres-Lam building with post-tensioned frames and walls, on the right.

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The flooring system consists of Timber-Concrete Composite (TCC) floors, spanning in the shorter direction and supported by gravity-only frames. The structural system has been designed to be as regular as possible, with longer spans achieved by both Pres-Lam frames and TCC floors which keep the same direction at each floor unlike the CLT building. The vertical supports within the floor area are very few, and no internal walls have been placed. Therefore, a free and flexible architectural internal layout is possible. LVL timber with a flexural strength of 44 MPa has been used for the Pres-Lam frames, while the walls are made of C24 cross-laminated timber. The gravity system and the TCC floor joists consists of glued laminated timber Gl24h. Indeed, LVL offers high resistance specifically in the perpendicular-to-grain direction, in addition to the parallel-to-grain direction, when compared to Gl24h or Gl32h laminated timber, which makes it a preferred choice for the high-performance Pres-Lam frames. As far as the reinforcement is concerned, 7-wire strands have been considered for the post-tensioning within the frames, with a nominal area of 150 mm^2 and a tensile strength of 1670 MPa. Internal unbonded post-tensioned threaded bars have been conversely used for the walls, with a nominal diameter of 40 mm and a tensile yielding strength of 835 MPa. The external Plug&Play fuse-shaped dissipaters are made of S355 steel. The frames are designed using the Direct Displacement-Based Design (DDBD) approach [15], where structural members (e.g., section dimensions, number of post-tensioning tendons, and initial post-tensioning force) are sized to meet the drift limitation and internal actions associated to the Serviceability Limit State (SLS) which tends to govern the design in timber structures. Once the drift/deformability level of the structure at SLS are satisfied, the detailed design with the addition of the external Plug&Play dissipaters and the final verification at the ultimate limit state (ULS) is thus conducted. The building is located in the moderate seismic zone of Cervia (i.e., seismic zone 2 according to the Italian seismic hazard model), characterised by a Peak Ground Acceleration (PGA) of 0.17 g. A soil class type C and an Importance Class II (i.e., residential building) have been considered [16]. Both frames and walls are designed for a target drift of 0.4% at SLS and 1% at ULS. The final cross-sections resulting from the DDBD are illustrated in Fig. 2. The number of post-tensioned strands within the frames decreases at upper floors, with four tendons at the first and second floor, three at the third floor, and two tendons at top floor. The LVL beams and columns thickness is made by gluing together five laminations, each 81 mm thick, coherently with the production limits for this material. The central lamination is separated in two portions to accommodate the hole for the post-tensioning tendons.

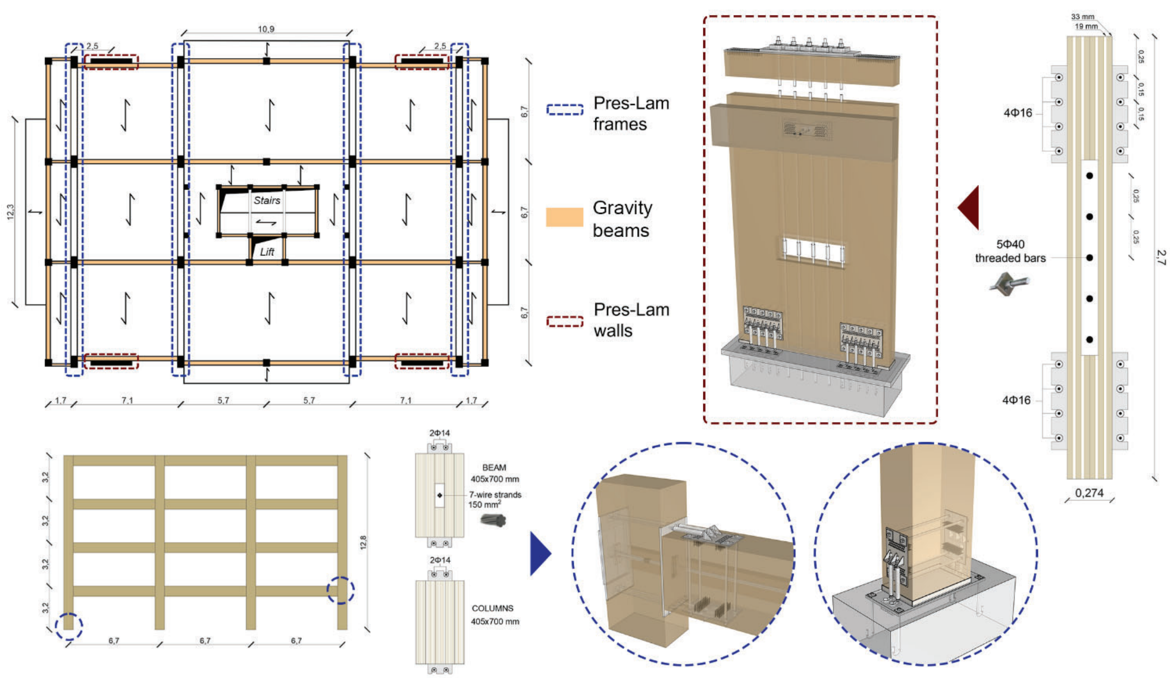

Figure 2. Structural layout of Pres-Lam buildings, including detailed views of post-tensioned frames equipped with Plug&Play dissipaters, and post-tensioned walls featuring a pinned connection to the diaphragm.

Similarly, for the CLT walls, the hole for the threaded bars is created by gluing together two 5-layered panels, each with a central cut on the internal side. All the connection details of the building structure have been detailed-designed, regarding both the LLRS (i.e., Pres-Lam frames and walls) as well as the gravity-only frames and the TCC flooring system. Specifically, as far as the beam-column and column-to-foundation joints of the Pres-Lam frames are concerned, the plates and fasteners for anchoring the dissipaters, the post-tensioning anchor plates in the external joints, and the anchoring at the foundation levels have been designed. The reinforcement perpendicular to grain in the columns have been provided by means of internal epoxied threaded rods, while a steel corbel with rubber bearing strip has been considered as the shear key at beam-column interface. The diaphragm-to-wall connection has been designed as well, consisting of the so-called "bow-tie", capable to maintain hierarchy of strength in the local failure mechanisms and distributing the loads through steel-to-steel connection and then steel-to-timber multiple connections. This vertically slotted pinned connection allows to transfer the horizontal forces from the floor to the wall, while preventing the transfer of gravity loads. The collector beam of the diaphragm is connected to the walls using a number of pins resisting the floor shear force, which are vertically restrained at the joist level but not on the wall side, allowing to accommodate the uplift of the wall during an earthquake without causing displacement incompatibility. All the abovementioned details have been designed following the Eurocodes and the New Zealand Standards. The TCC floors and gravity frames have been detailed designed as well, providing hinged connections for the beam-to-column joints using slotted holes able to accommodate the displacement imposed by the Pres-Lam structure without any damage.

3 – SEISMIC PERFORMANCE OF THE PRES-LAM STRUCTURE

The seismic performance of the Pres-Lam frames and walls within the project is evaluated by implementing a lumped plasticity model of the structure [17] and consequently performing numerical non-linear static (pushover) analyses (NLSA). Specifically, the Capacity Spectrum method (CSM) [18] has been developed to identify the performance points of the structure at SLS, ULS and Maximum Considered Earthquake (MCE) limit states. by comparing the Capacity curve and the seismic Demand within an ADRS (Acceleration-Displacement Responde Spectum) domain. The effective damping of the structure has been calculated through an area-based approach on the hysteresis cycles resulting from push-pull analyses. The drift values at the effective height of the equivalent SDOF system for the Pres-Lam frames and walls, corresponding to each performance point, are plotted along the capacity curve in Fig.3. For all the LS, these values are lower than the design drift used as input for the DDBD. Both the Pres-Lam frames and walls exhibit high inherent re-centering capabilities - already in their quasi-static behaviour - with nearly zero residual displacements, as demonstrated by the results of the cyclic non-linear static (push-pull) analyses also shown in Fig. 3. The curves show the progressive loss of the external dissipaters across the frame's sections and at the wall's base section, with the remaining contribution coming solely from the post-tensioned reinforcement, which is characterized by a non-linear elastic behaviour.

4 – COST EVALUATION

The Bill of Quantity (BoQ) is a valuable tool providing a comprehensive breakdown of the quantities and description of work to be carried out in a construction project, along with the corresponding costs.

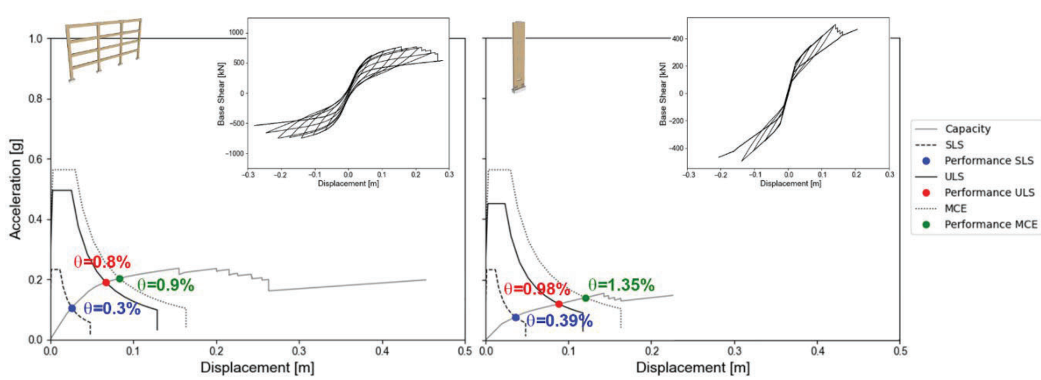

Figure 3. Numerical pushover curve of the Pres-Lam frames, on the left, and walls, on the right, with the detection of the performance points and the corresponding drift values at the different limit states. The hysteretic capacity curves obtained from non-linear push-pull analyses are also shown.

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In this project it has been developed through a joint effort between industry and academia, by also involving third-party industries and manufacturers for the different elements and materials used within the Pres-Lam case-study building. The costs herein presented, although being representative of the current construction market in Italy for low-damage timber buildings, apply specifically to the building developed in this study and may not accurately reflect the construction cost of a different building utilizing the same technology. However, as the case study represents the typical construction approach for Pres-Lam buildings, the price serves as a reliable reference for such constructions in Italy. The construction cost of the Pres-Lam building has been assessed based solely on the "shell and core" (i.e., just the structural skeleton), excluding façades, internal partitions, finishes, services, and design-related costs. However, the evaluation includes the manufacturing, supply, transport and installation on-site of all the building elements, including all the fasteners employed in the connections. The price for supplying and transport the CLT for the Pres-Lam walls within the building has been considered equal to 800€/m^3, plus 11€/m^2 for the pre-assembly of two 5-layered panels to obtain the central void for the post-tensioning cables. The cost used for the laminated Glulam timber of the gravity frames is equal to 1000€/m^3, while the LVL for the Pres-Lam frames has been rated 1600€/m^3 including also the pre-assembly of multiple elements with adhesive to obtain the final sections. The supply, transport, installation and post-tensioning of the approximately 13 meters long threaded bars for the Pres-Lam walls has been estimated by the supplier as approximately 34000 €, while the cost of the 7-wire strands has been evaluated from the regional price list and, therefore, refers to precast concrete. However, the difference has not been considered significant. The cost related to all the tailored plates for the Pres-Lam structure has been evaluated equal to 7€/kg by the steel supplier, while the fuse-type Plug&Play dissipaters manufacturing is on average around 10€ each, which further confirms the cost-effectiveness of such replaceable devices. On the other hand, the total cost of all the fasteners employed within the project is around 100’000 €. The cost of installation has been evaluated equal to 600€/m^3 for the Pres-lam frames, 16.5€/m^2 for the walls, and 300€/m^3 for the gravity Glulam frames. The TCC floor components (i.e., Glulam joists, timber sheathing, and concrete slab) has been considered to be installed separately on-site, by using the regional price list for the supply and installation of each element. Alternatively, the floor can be supplied as a pre-fabricated system with the concrete topping cast in the production facility. It is worth saying that the prices considered for the prefabrication and installation of the low-damage structure significantly reflect the industry uncertainty in predicting the cost of a new system which has never been built in the country. The construction process considered for the Pres-lam structure within the building is illustrated in Fig. 4. The time required to lift the structure has been estimated as 5 days for the frames and 1 day for the walls. The cost of the crane needed to lift both systems is estimated at 1’000 € per day. The post-tensioning of both the frames and walls have been considered to be carried out once the structure has been lifted. This involves the use of scaffolding to allow the workers to reach the higher floors of the Pres-Lam frames and the top section of the walls. Alternatively, as typically in a number of real on-site implementation worldwide, the Pres-Lam structure can be post-tensioned on the ground and then lifted into place, therefore saving the cost of the scaffolding. It is important to note that, in this case, the building's height allows for a single panel to reach the wall’s full height. However, if the height exceeds 13 m, multiple panels may be required for transport, necessitating the design of proper splice horizontal connections between them. Based on the BoQ, the total construction cost of the building structural skeleton was estimated to be equal to 1’328’030 € (Table 1), which corresponds to a rate of 594 €/m^2. As illustrated in Fig.5a and listed in Table 1, approximately one-third of the total costs is attributed to the Pres-lam frames, when including material supply, manufacturing and installation, followed by the TCC flooring system. Regarding the various types of timber and materials used in the building, Glulam accounts for 28% of the total cost (Fig. 5b), representing the highest proportion among the engineered timber products used in the project. This is due to the greater number of gravity frames and floor joists compared to the Pres-Lam structure. The LVL follows, primarily because of its highest price rate and the absence of LVL production plants in Italy, with the nearest facility located in Germany. The LVL elements for the Pres-Lam frames are assumed to be produced at the German factory and subsequently sold to the

Table 1. Estimated total cost of the Pres-Lam building and its different structural components.

Components	**Cost (€)**
LVL Pres-Lam frames	457’266
CLT Pres-Lam walls	178’555
Glulam Gravity frames	292’877
TCC floors and stairs	399’332
TOTAL	1’328’030

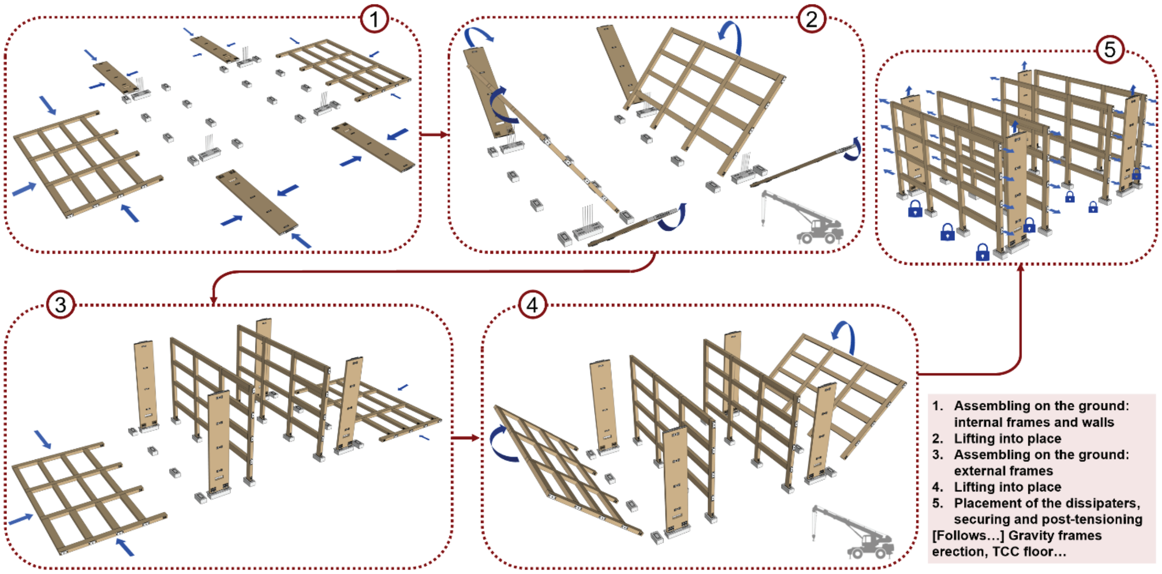

Figure 4. Construction process of the Pres-lam frames and walls.

company involved in the project, which is responsible for assembling and constructing the structure. Consequently, the cost also includes the company's profit margin. Nevertheless, the highest overall percentage of material cost is represented by the steel elements (i.e., plates, fasteners and dissipaters used for the connections). This cost might be reduced by optimizing the dimensions of the plates used for the Pres-Lam connections. Finally, when considering the various production and construction stages, the highest cost percentage is attributed to the supply, processing, and transport of materials, which together account for more than 50% of the total cost (Fig. 5c). Since most of the prices in the BoQ combine these three stages, it was not possible to calculate the precise percentage associated with each one. The construction cost of the original CLT building, completed in early 2024, was 908'500 € (406 €/m^2). The difference compared to the new low-damage timber building is around 420'000 €, which can be considered moderately high [19]. As previously noted, the high cost estimation may stem from industry bias and uncertainty towards the adoption of a new and innovative system, as well as the fact that the estimate is based on market prices - for academic purposes - rather than a competitive bid. Additionally, the cost of timber is heavily influenced by economies of scale, which could further impact pricing in the absence of widespread production and adoption. It is worth saying that the cost comparison does not take into account the sub-structure (i.e., foundations), which will necessarily be slightly different – yet not remarkably - between the Pres-Lam and CLT structural systems.

5 – PROJECT SUSTAINABILITY

A selected cradle-to-grave Life-Cycle Assessment (LCA) was performed for the original CLT building and the re-designed Pres-Lam building. In fact, the operational energy use stage was herein not considered, or better assumed for simplicity to be identical, as energy simulations have not been covered within this study.

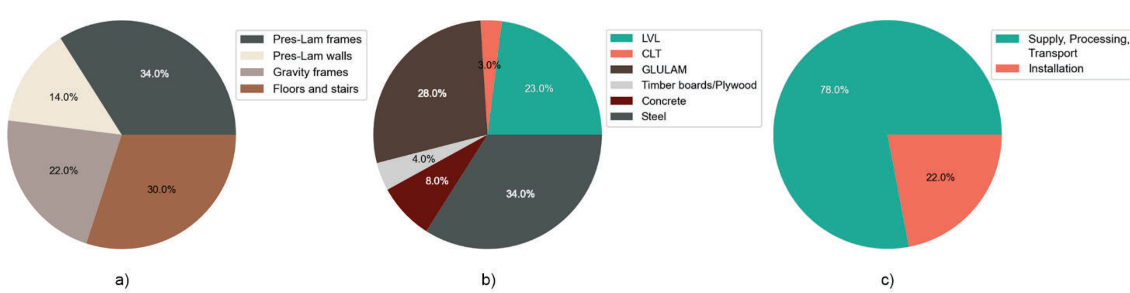

Figure 5. Percentage of costs related to a) Different structural systems within the project, b) Different materials employed, c) Production and construction stages.

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To be consistent with the products used to evaluate the construction cost of the building, manufacturer-specific EPD of each material were collected using the database of One Click LCA. The results are expressed in terms of Global Warming Potential (GWP), i.e., kgCO2 equivalent. Since only the timber-based structural system of the building is considered, without taking into account the non-structural components (i.e., facades and internal partitions) as well as the sub-structure, it has been deemed interesting to include also the biogenic carbon in the results. Biogenic carbon is the carbon that is stored in biological materials, such as timber, during the growth stage and then kept as long as the material is used. This means that, if incineration is avoided as the End of Life scenario, the carbon stored by the timber product is never released back to the atmosphere, creating an overall positive balance of environmental impact. As shown in Fig. 6a, the LCA results displays a higher contribution in carbon emissions of the Pres-Lam building over the CLT one, mainly due to the use of concrete in the TCC floor as evident from Fig. 6b where this material is neglected from the calculation. The environmental impact of concrete is also related to the transport and waste processing stages, which decrease when concrete is avoided. Nevertheless, the carbon stored by the low-damage building throughout its life cycle is significantly higher than the traditional CLT building, resulting in a net positive outcome. The environmental footprint of the Pres-Lam building is influenced by the use of various types of engineered timber within the structure, as well as the need to transport LVL from outside the country. As far as the End-of-Life of the building components is concerned, re-use has been considered as the final scenario of all the timber elements within the low-damage building, since both the modular, and demountable, Pres-Lam structure and the gravity frames have been designed to properly withstand earthquakes with negligible damage. In contrast, the EoL phase of the CLT building is associated with a higher GWP due to the need to replace panels that may be damaged by the connection systems during an earthquake. To further highlight the benefit of using a modular and low-damage timber structure as the Pres-Lam system, the building circularity of the two alternatives has been evaluated. Circularity in building construction focuses on designing and managing buildings to minimize waste and maximize resource efficiency throughout their lifecycle. This approach emphasizes the use of sustainable materials, modular and flexible designs, and strategies for reduce, reuse, recycling (when necessary), and repurposing at the end of a building's life. To define the circularity score of each building, the "Building Circularity Tool" available in the One Click LCA software has been used. This tool takes into account the various EoL scenarios selected for building materials and components during the LCA process, assigning a score that reflects the circularity level of each specific scenario. More specifically, the calculation considers the percentage of materials/components reused as material in new project, the percentage of materials that can be recycled, the percentage that can be downcycled (i.e., materials repurposed into new products characterised by a lower strength), the percentage of materials used for energy production through incineration, and the percentage of materials destined for landfill disposal. Weighting factors are assigned to each scenario, with a factor of 1 for re-using and recycling, 0.5 for downcycling and use as energy, and 0 for disposal. The final Building Circularity Score is the average of the materials recovered

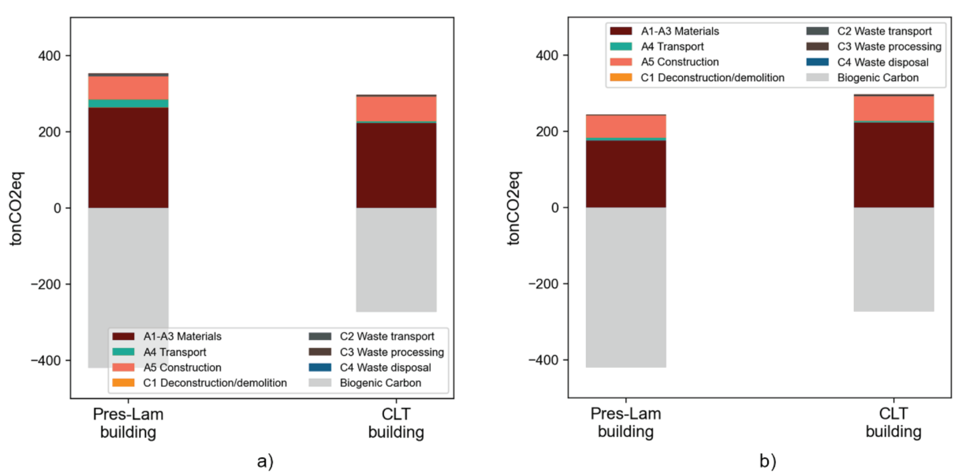

Figure 6. Cradle-to-grave Global Warming Potential (GWP) of the two building when a) concrete is considered, b) concrete is neglected.

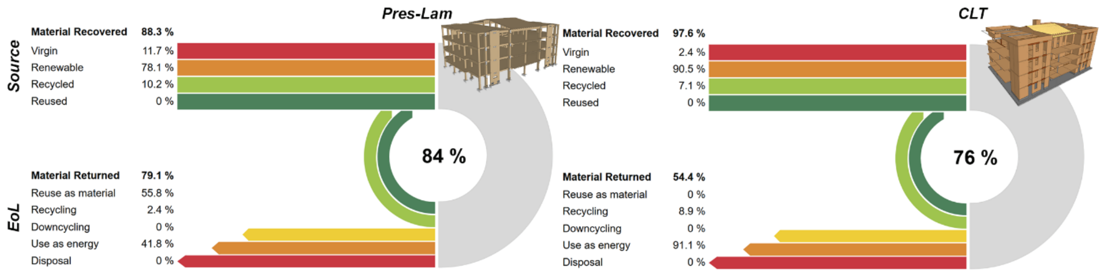

Figure 7. Building Circularity Score associated to the Pres-Lam (on the left) and CLT (on the right) building based on their material sources and EoL scenarios.

(i.e., amount of circular materials used as input within the project) and the materials returned (i.e., materials with circular EoL scenarios), and it is based on the calculation period considered for the specific building (i.e., 50 years if conventional buildings are considered). In this project, the material source specified in the EPDs used for the LCA have been applied to the building components, while the EoL scenarios are determined by the design. As illustrated in Fig. 7, the circularity score of the Pres-Lam case-study building is higher (better) than that of the original CLT building, despite the greater percentage of source materials recovered in the traditional building. The higher overall score of the Pres-Lam building is due to the employment of the low-damage technology which allows to reuse (either as material or component) the modular structural members at their EoL. Conversely, wood incineration and recycling has been chosen as the most suitable EoL option for the cross-laminated panels in the CLT building, as they are custom-made for the specific project and are likely to experience damage if any earthquake occurs during their lifespan. The Pres-Lam technology allows for the integration of the Design for Assembly (DfA) and Disassembly (DfD) principles within the building design. These two critical approaches aim at improving construction efficiency and sustainability introducing the circular economy principles in modern building design. They focus on designing components that are easy to handle and fit together, and that can be easily disassembled, recovered and reused. In other words, they can be embraced in the overall concept of Design for Adaptation, avoiding building obsolescence and the associated environmental and cost impacts of resource consumption and material waste by enabling future changes to adapt and respond to evolving needs. The main shortcomings in applying these strategies to conventional timber buildings are related to their design as individualistic buildings, where parts are hard to reuse, and the fact that the connections are designed to experience damage embedding the timber elements. This would require high building performance to withstand any catastrophic event that may occur during their lifespan. The Pres-Lam structural system, on the other hand, enables the reuse of parts due to its modularity, the reversibility of the connections, and the high seismic performance. By preventing damage to the structural members, the entire system can be fully disassembled and reused (either in a different building or in the same building), thereby significantly extending the building's service life. By also providing large open spaces, the internal architectural flexibility allows the building to be repurposed for different functions. This not only reduces the environmental impact associated with demolition but also eliminates the need for the construction of new buildings.

6 – ARCHITECTURAL FLEXIBILITY

Based on the considerations made above, the adaptability of the Pres-Lam case-study building is demonstrated by changing the architectural layout of the internal spaces from a residential building (Fig. 8a) to an office building (Fig. 8b). The layout of the four residential floors has been kept identical to the one originally designed for the CLT building. Only minor changes have been made to the windows due to the presence of columns and walls on the building's envelope. The original CLT lateral-load and gravity-load resisting structure includes the thick walls between each apartments, making impossible to completely modify the internal layout, except within the single apartment (Fig. 9a). In contrast, the internal walls of the Pres-Lam building are simple partitions, which can be made using gypsum-based panels (with additional insulation when dividing two apartments). Therefore, the large open space of the low-damage building allows for a complete redefinition of the internal space (Fig. 9b). The service blocks have been kept in the same place when re-designing the plan, while the other spaces now host open offices, meetings rooms, reception, coffee areas, lunch room, director's office, and so on. This represents just an example of internal office layout; the open plan offers a variety of flexible configurations.

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Figure 8. a) Internal distribution of the second floor of the residential Pres-Lam building; b) Modified internal layout from residential to office space.

7 – CONCLUSIONS

In this paper, a real case-study building was presented by re-designing a residential platform-type building located in northern-central Italy using Pres-Lam frames and walls. The project was developed through a collaborative effort with industry, enabling a comprehensive design of the low-damage structural system and a feasibility study on its implementation. The seismic performance of the low-damage structure, designed using the Direct Displacement Based Design (DDBD) procedure, was assessed through non-linear static (pushover) analyses implementing the Capacity Spectrum Method (CSM), which provides inter-storey drift values at various limit states. The acceptable drift levels and the re-centering capability with negligible residual displacements of both frames and walls, assessed through cyclic non-linear static analyses, confirm the system's high performance and solid design. A cost evaluation of the new Pres-Lam building was conducted through a Bill of Quantity (BoQ) analysis, considering only the super-structure. The building structural skeleton was estimated to cost approximately 400’000 € (46%) more than the original CLT building. Arguably, this cost difference can be inherently, though possibly partially, attributed to industry uncertainty and bias toward a new system that has never been built before in the country, as well as the use of different types of engineered timber, some of which was sourced from outside Italy. By conducting a Life-Cycle Cost analysis of the building, the higher initial cost could be offset by larger savings during its lifetime due to the reduced economic losses caused by earthquake-induced damage. A Life-Cycle Assessment (LCA) was also performed on both the Pres-Lam and CLT buildings, highlighting the low environmental impact of both solutions. The Pres-Lam system, however, resulted in a higher negative net value for Global Warming Potential (GWP), primarily due to greater Biogenic Carbon storage. Moreover, the potential to reuse the building's low-damage components supports the implementation of circularity principles in building design, as demonstrated by the higher Circular Building Score of the Pres-Lam building compared to the CLT building. By using damage-control technologies, the building’s elements can be repurposed at their End of Life in a different or the same building, consequently extending its lifespan.

Figure 9. The different flexibility of the internal space between a) the Pres-Lam building and b) the CLT building.

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This is demonstrated in the project by the redesign of the internal layout, transitioning from residential to office spaces—an option that would be difficult to achieve in the original CLT building, characterized by rigid interior spaces. Such a feature would be highly appreciated in a Value Engineering market evaluation. The case-study building presented in this paper - together with low-damage and energy-efficient facade systems - demonstrates that, through a collaborative partnership between academia and industry, the implementation of Pres-Lam buildings can represent a significant step toward a sustainable and resilient built environment. By incorporating Design for Adaptability principles, these buildings address the growing challenges posed by an ever-evolving society through an advanced and cost-effective solution.

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