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Adaptive Timber Exoskeletons: Sustainable Seismic Retrofitting with CLT Panels

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ABSTRACT: The extensive renovation of existing buildings is essential to mitigate seismic risk and environmental impacts. To prioritize safety and sustainability, retrofit strategies should minimize disruption and adopt a Life Cycle Thinking (LCT) approach to reduce long-term costs and impacts. Timber-based materials, particularly Cross-Laminated Timber (CLT) panels, offer significant potential for integrated retrofitting due to their mechanical, thermal, and environmental properties. This paper explores timber exoskeletons as a possible solution for seismic retrofitting, emphasizing the central role of structural configurations and connections. Exoskeletons, as external lateral force resisting systems, provide relevant performance and displacement control by collecting the building inertia and transfer forces at floor levels and transferring actions to the foundations. The design process emphasizes damage control at the Life Safety Limit State (LSLS), for which adaptive solutions appear to be optimal. Numerical simulations using a reference 3-story RC building demonstrate, when applicable, the superior performance of shell configuration. Overall, timber exoskeletons represent a promising solution for sustainable seismic retrofitting of low-rise buildings.

KEYWORDS: Timber exoskeleton, Life Cycle Thinking (LCT), Cross-Laminated Timber (CLT), Adaptive systems

1 – INTRODUCTION

The Italian building stock consists mainly of RC or unreinforced masonry structures built without specific seismic-safety or energy-efficiency regulations, and now it is inadequate to the current standards. This implies important impacts at the environmental level, due to greenhouse gas emissions; at the economic level, due to the operating and maintenance costs of poorly performing systems; and at the social level, in terms of both living comfort and quality of the urban context and safety in case of exceptional events such as earthquakes.

The deep renovation of the existing building stock is critical, as highlighted by the recent European "renovation wave" roadmap [1] and by the "New European Bauhaus", as demolition and reconstruction is not a viable solution on a large scale. To reach the ambitious EU goals, a comprehensive transformation of the building sector and the concept of building renovation, inspired by the Life Cycle Thinking (LCT) approach is required [2]. When adopting the LCT approach, additional design principles such as eco-efficiency, safety, resilience, and equity, as well as criteria, such as prefabrication, standardization, off-site production, are defined to enable the conceptual design of new sustainable retrofit techniques and overcome barriers to the renovation.

One of the major challenges in renovation is avoiding the relocation of inhabitants, which has led to the concept of employing seismic retrofitting systems built from outside of the building, in the case of non-listed buildings of no architectural value. Among them, exoskeletons can provide higher structural performances while minimizing environmental, social and economic impacts; they may also be conceived to be easily integrated with energy and plant efficiency systems and implemented with customizable architectural finishes [3].

In this context, the use of timber-based materials allows, for the reduction of the environmental impact while, simultaneously, leveraging the advantages offered by timber 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.

In this paper, the use of CLT panels for seismic retrofitting of existing buildings will be explored with focus on exoskeletons. Advanced structural schemes, design criteria and connection systems will be analysed.

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2 – BACKGROUND

Among the most popular structural materials, timber stands out as the one with the longest history, being a natural material that is easily available, workable and transportable. Considering the current needs of the construction industry, timber still offer significant advantages compared to other structural materials. In fact, in addition to its excellent mechanical properties, particularly its strength-to-weight ratio, outperforms other materials in terms of thermal performance and environmental impact.

Nowadays, the wood industry has experienced significant advancements, and every stage of production is subject to specific controls and regulations. This has led to a general standardization of materials, production processes, and end products, as well as improved forest management practices to ensure the sustainability of wood as a renewable raw material. New processing techniques are increasingly oriented optimizing the use of wood by moving from structural elements made of solid timber to "engineered timber" products, such as Cross Laminated Timber (CLT). These innovations address limitations related to geometry and defects of the base material while minimizing production waste [4]. As a results, it is possible to produce large layered panels suitable for the construction of load-bearing walls and slabs, providing excellent structural performance both when loaded in the plane and in the out-of-plane.

This technology is widely used in the construction of timber buildings, offering high living comfort and structural performance thanks to the excellent qualities of the system [5]. It enables the prefabrication of wall and slabs in the factory, which are then assembled on-site in a short time using platform or balloon techniques. The process is further streamlined by standardized mechanical connections, primarily consisting of pre-drilled metal plates and small-diameter fasteners such as nails, screws, and dowels.

In recent years, the excellent mechanical properties of the material and its compatibility with dry construction techniques have encouraged the use of CLT for the retrofit of existing buildings. Some applications involved the strengthening of wooden floors of existing buildings, in which CLT panels have been used to create extrados reinforcements that can simultaneously stiffen the floor joists for gravity loads and create floor diaphragms capable of resisting horizontal loads and, thanks to appropriate connections, prevent the out-of-plane mechanism of masonry walls [6].

The use of CLT panels has also been explored for the seismic strengthening of vertical structures in existing buildings. The proposed solutions differ depending on the structural layout of the buildings (masonry walls or RC infilled frames), the application side (interior or exterior) and the structural organization of the system (short span panels to reinforce individual structural elements, long span panels on new foundation system to create new seismic-resistant elements). Although these solutions differ in terms of invasiveness and performance pursued, they demonstrate the potential of CLT for the integrated retrofit of existing buildings [7-12].

3 – CLT EXOSKELETONS

Exoskeletons are structural systems, which can encompass several geometric configurations, arranged externally to the building [13-14]. They consist of a vertical structure, engineered with either bracing frames, walls, lattice elements, panels or hybrid systems; connections to the existing building, usually at the floor level; and a foundation system, which can either be independent or integrated with that of the building.

Exoskeletons can be divided into two macro categories: (i) shear wall systems are those featuring shear walls applied on individual façades and designed to resist horizontal forces acting in the in-plane direction. (ii) Shell systems, on the other hand, are characterized by structural elements distributed along all façades, connected at the corners, that cover the entire building envelope and behave like a structural involucre. These elements work together to resist horizontal actions, leveraging their geometric configuration for improved structural performance.

Exoskeletons are conceived as additional structural system controlling the seismic response of the retrofitted building and are particularly suitable for damage control-oriented applications of multi-objective Performance-Based and Life Cycle Thinking-Based Design [13].

The design of structural systems made of CLT panels can represent a significant innovation for developing integrated and sustainable interventions by employing exoskeletons of both shear wall and, especially, shell type. A crucial aspect lies in the conceptual design of the intervention, properly balancing the stiffness and strength of the exoskeleton, and designing the structural details of the connections and foundations targeting both energy dissipation and compliance with Capacity Design. The feasibility of the intervention must be first verified by evaluating the in-plane capacity of the existing floors and their ability to behave like diaphragms transferring the seismic actions between the existing building and the

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exoskeleton [15], as well as by verifying that the strength of the system is not jeopardized by possible irregularity of the façades and of the layout of the openings. For these reasons, timber exoskeletons may be unfeasible for high-rise buildings, where the expected base shear would be excessive, or for buildings with elevation irregularities (pilots floor, misaligned openings, widespread presence of balconies, ...) where panel continuity cannot be guaranteed. Many of these situations can be addressed by adopting hybrid timber-steel systems, with steel profiles coupled with CLT panels to streamline the transfer of actions at the most critical points of the structure where, for example, geometric irregularities might induce stresses concentration [11].

3.1 STRUCTURAL CONFIGURATIONS

When shear wall systems are adopted, CLT panels may be designed as single or coupled shear walls. By employing single walls (with $B \times t$ cross section), the system behaves as a cantilever beam with point loads at each floor, subject to bending and shear stresses. By enforcing the capacity design, the structural performance of a single CLT wall is associated with the bending capacity at the foundation interface ($M_{Rd,sw,i}$), given by the sum of the tensile strength of the hold-down connections (T), and the magnitude of stabilizing vertical loads (N), multiplied by their lever arms z, and e, respectively (Fig. 1), which is designed to be less than the flexural strength offered by the CLT panel cross section ($M_{Rd,CLT}$):

$$M_{Rd,sw,i} = Tz + Ne < M_{Rd,CLT} = f_{md}Bt_{net} / 6 \tag{1}$$

where f_{md} is the bending strength of the CLT, depending on the timber strength class, B is the length of the panel base and t_{net} is the effective panel thickness, consisting of the sum of the layers oriented in the direction of the stressing actions.

According to (1), to increase the overall strength different solutions can be considered: tensile connections with higher capacity may be used [16], the lever arm can be increased through the use of lateral columns [17], or prestressing systems with unbounded steel tendons, that provide a high stabilizing load and self-centring behaviour, can be employed [18].

The structural performance can be further improved by employing coupled shear walls, which consist of two or more CLT panels connected by coupling elements capable of transferring both bending and shear forces. This configuration transforms the structural system into a frame-like scheme. As a result, for the same footprint as single walls, the strength and stiffness of the system are greatly increased:

$$M_{Rd,cw} = \Sigma\, M_{Rd,sw,i} + \Sigma\, F_{c1,i} d_{1n} \tag{2}$$

where the additional bending contribution is given by the coupling action ($\Sigma\, F_{c1,i}$), multiplied by the lever arm (d_{1n}), evaluated as the distance between the centroid axis of the first and last panel along the reference alignment. The coupling elements between vertical walls can be located in the areas between existing openings, considering that the maximum coupling contribution increases with the height of these elements.

Shell systems may be the most challenging to realize but also the most structurally efficient, since they are distributed along the entire perimeter of the building and include connections between orthogonal elements as well; this allows maximizing the bending strength and stiffness of the exoskeleton. Shell systems have the advantage that they can be organized in different ways according to required performance target and geometric limitations. In fact, longitudinal walls can be designed to resist only shear actions ($M_{Rd,sw,i} = 0$), entrusting bending actions to corner columns, thus reducing the number of base connections and the resulting actions on the foundation system (Fig. 2), or they can also contribute to bending resistance as in the previous cases (Fig. 3), further increasing the overall performance:

$$M_{Rd,shell} = \Sigma\, M_{Rd,sw,i} + \Sigma\, F_{c2,i}\, L - (\Sigma\, F_{c2,i} - \Sigma\, F_{c1,i})\, d_{1n} \tag{3}$$

Where $\Sigma\, F_{c2,i}$ is the coupling action transferred by the connections between orthogonal façades and L is the length of the façade. It is worth noting that in (3), if the connection between adjacent panels (C1) and orthogonal panels (C2) are designed to transfer the same shear action, the term ($\Sigma\, F_{c2,i} - \Sigma\, F_{c1,i}$) is equal to 0.

The design of CLT shell systems offers two possible layouts for the arrangement of the panels with respect to the façade: either vertically (balloon-type), as in the construction of single and coupled walls, or horizontally (platform-type), with panels spanning the length of the façade and a height equal to the interstory. These two solutions differ in terms of panel processing and connection layout. Specifically, in the first case, monolithic walls can be used either coupled with bands above and below the windows or shaped to contour existing openings (Fig. 3). In the second case, the panels must be perforated at the planned openings, and the connections are placed along the horizontal interface between the upper elements (Fig. 2).

The platform-type solution, can offer greater strength and stiffness than the balloon-type solution, provided by the

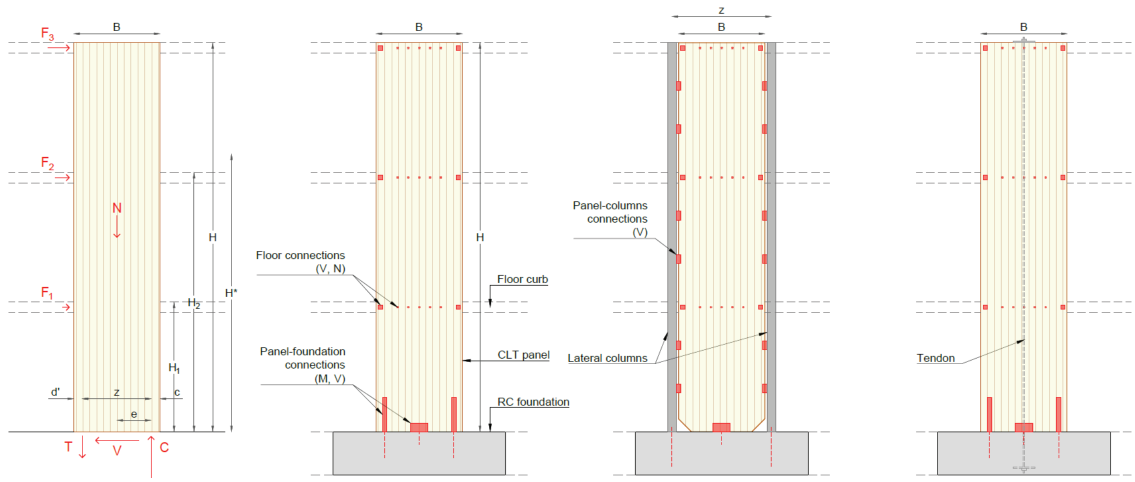

Figure 1. Exoskeleton with single wall CLT panels: geometric characterization and possible structural configurations.

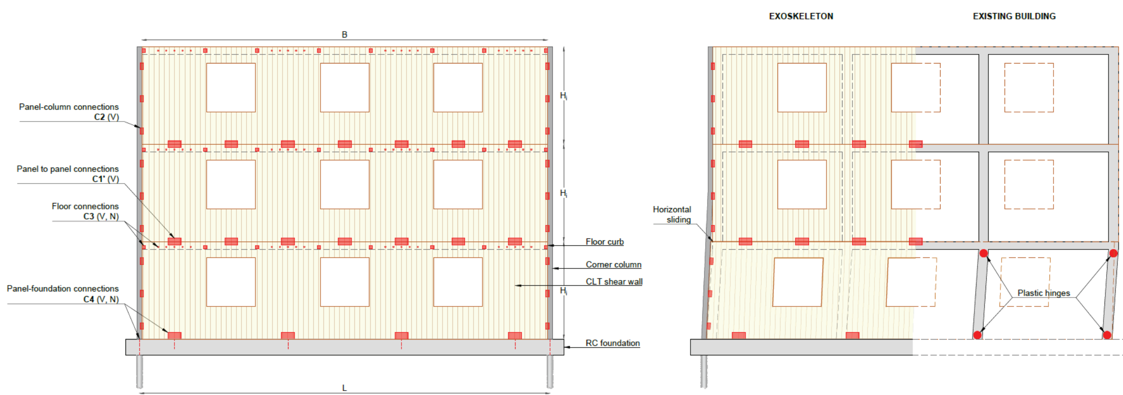

Figure 2. Shell exoskeleton with CLT panels in platform-type configuration: structural details and expected collapse mechanism.

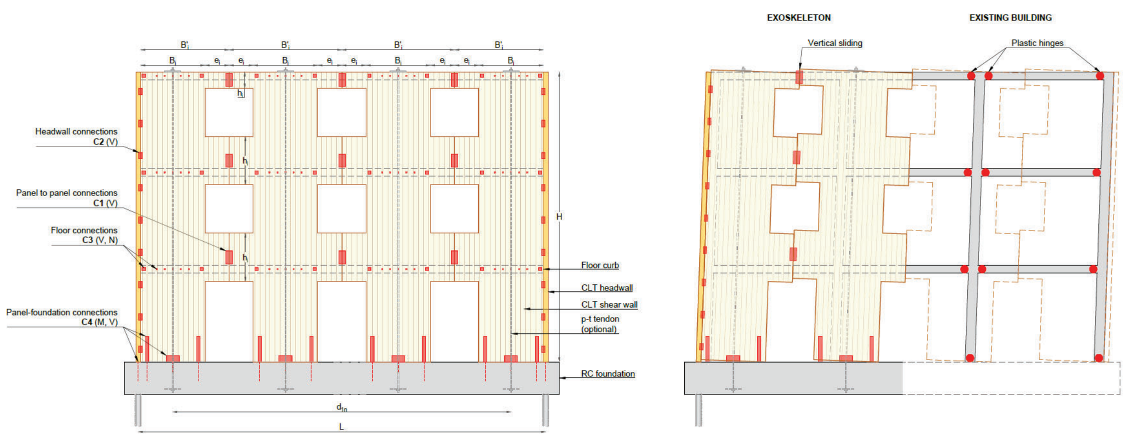

Figure 3. Shell exoskeleton with CLT panels in balloon-type configuration: structural details and expected collapse mechanism.

monolithicity of the panels around the openings. This, on the other hand, implies a special attention in the evaluation of the stresses induced in the notched sections of CLT panels that may be subject to brittle failure [19]. In addition, the connections between panels along the horizontal interfaces at each floor may involve in relative sliding that, once maximum design shear is reached, results in local deformations that can lead to the activation of a soft story mechanism in the existing building (Fig. 2), which will have to be carefully evaluated according to the ductility offered by the existing vertical elements. On the contrary, the presence of monolithic vertical panels allows for regularizing the deformation of the building leading to the onset of a collapse mechanism involving all stories, which is associated with increased ductility (Fig. 3). In addition,

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residual displacements can be managed by adopting recentring systems. Considering these aspects, the platform-type solution, due to its greater stiffness, is ideal in presence of small openings and corner columns, with CLT panels subjected mainly to shear actions. In contrast, the balloon-type solution is optimal when it is intended to achieve higher dissipative capacity and self-centring behaviour.

3.2 ADVANCED DESIGN CRITERIA

When designing exoskeletons from the LCT perspective, it is advisable to define structural design criteria that are more demanding than those required by actual standards and oriented towards multi-objective Performance-Based Design [13]. For example, by introducing specific criteria on damage control at LSLS, it becomes possible not only to ensure the safety of inhabitants but also to limit damage in structural and non-structural elements, thereby lowering the impacts in the post-event, pursuing resilience.

Reducing the maximum drift implies however increasing the stiffness of the structure and consequently the maximum expected accelerations; in that case, it also becomes important to make provisions against the "acceleration sensitive" elements inside the building (diaphragms, stairwells, foundations, plants, furniture, equipment, countertops, ...) for which it will be necessary to introduce appropriate connection systems or, where possible, damping systems.

In addition, the management of residual drift also assumes great importance since the presence of permanent deformations can compromise the repairability of components and adversely affect non-structural elements such as cladding, doors, windows.

Another significant aspect of structural resilience involves the use of dissipative elements as "structural fuses" to ensure reparability. These elements are designed to limit maximum stresses in other components and activate a ductile mechanism by localizing plastic deformations and dissipation of seismic energy. To achieve stable and efficient dissipative behaviour hysteretic, frictional or viscous systems should be preferred [20]. By positioning these elements in strategic and easily accessible locations within the structure, it becomes possible to ensure their easy maintenance and replacement after seismic events, minimizing costs and disruption time while preserving the integrity of the structure.

Exoskeletons can be designed to exhibit qualitatively different structural behaviours during a seismic event, depending on the characteristics of the new lateral force-resisting system, the features of the existing building, and the connections employed. In this perspective, the adaptive exoskeletons appear to be a highly effective solution, as they meet all the advanced criteria described. In fact, this solution, introduced with Pres-Lam system [18], allows for effective control the building's response limiting its damage during medium-to-high-intensity earthquakes by ensuring a self-centring behaviour; additionally, it offers a good dissipative capacity under high-intensity earthquakes, limiting the maximum acceleration and, consequently, the stresses in the structural and non-structural elements. If this concept is extended to coupled wall or shell exoskeletons with balloon-type configuration, designed such that the dissipative contribution at LSLS is offered by the connections between CLT panels, it is possible to obtain a capacity curve characterized by three distinct phases (Fig. 4): the first in which the system behave elastically, with no energy dissipation or damage; the second in which the couplers reach yield strength, triggering energy

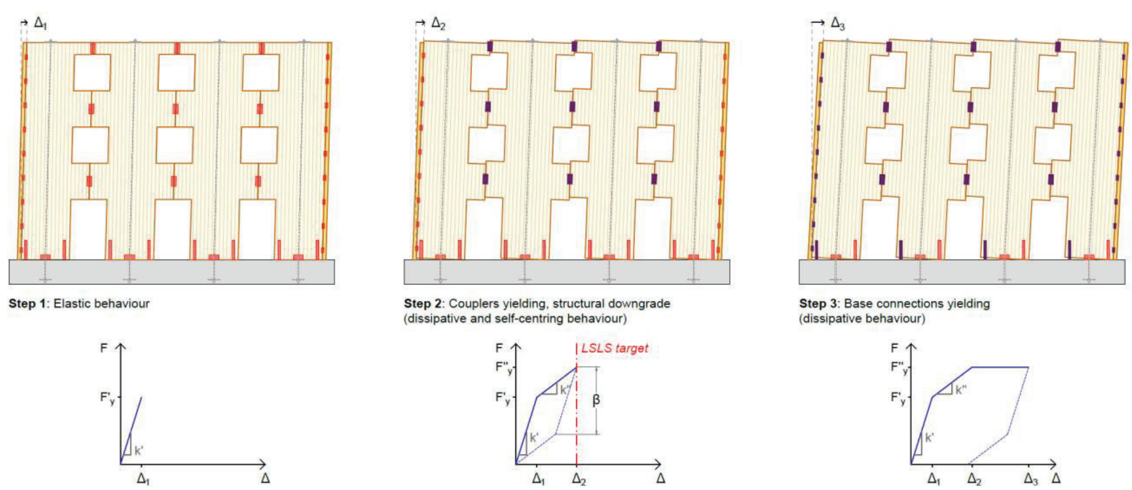

Figure 4. Concept of adaptive behaviour applied to a shell exoskeleton.

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dissipation and causing a downgrade of the structural system with a reduction in stiffness and a resisting and self-centring contribution provided by the connections at the base of the panels (including any prestressing action); and the third phase in which the axial connections at the base also reach yield strength, lowering the stiffness of the system and further increasing energy dissipation until collapse.

3.3 CONNECTIONS

The connection systems are crucial in the design of exoskeletons. From a structural point of view, connections between the building and exoskeleton transfer the seismic actions, may improve the out-of-plane behaviour of walls and infills, and may dissipate energy and guarantee the self-centring of the building after an earthquake if properly designed.

However, connections, not only play a key role from a structural point of view, but they are also enabling technologies for LCT design. They may ensure ease of assembly (considering construction tolerances), maintenance, integration, and disassembly of each component, thereby minimizing the operational impacts and extending their life cycle.

The main connections required for the design of an exoskeleton include: (i) connections with the existing building, (ii) connections with the foundation system, (iii) connections between adjacent panels, (iiii) connections between orthogonal panels (for shell systems). When required, connections can also be introduced between CLT panels and existing infills to prevent their out of plane flexural mechanism [9].

The capacity Design approach can be applied by considering CLT panels as rigid and over-resistant in relation to the connection system. On the other hand, each type of connection can be designed to exhibit either dissipative or over-resistant behaviour, depending on the design targets.

It is worth noting that traditional connections for timber structures are generally designed to transfer modest actions and involve many dowel-type connectors (nails, screws), that can offer limited dissipative capacity due to pinching phenomena [21]. When designing exoskeletons according to LCT criteria, however, it is necessary to limit the number of connectors while ensuring high structural performance and stable dissipative behaviour. In this perspective, traditional connection systems are often inadequate, and many studies have been performed to develop high-performance hold-down systems [19] and couplers [22-23], although in most cases the applications are targeted at the construction of new timber buildings.

4 – APPLICATION EXAMPLE

To compare exoskeleton structural configurations and apply the design criteria, a case study RC building was developed, representative of post-World War II residential construction, characterized by regularity in geometric-structural organization, with plan dimensions (19x10.5) m^2. The geometry of the reference building was designed to have maximum regularity in plan and elevation, consisting on 3 floors above ground with a constant interstory height of 3.10 m and an arrangement of openings (doors and windows) along the perimeter such that a shell could be organized with CLT panels all having the same width (B), i.e., 2 m for the X direction (6 panels for each façade) and 2.5 m for the Y direction (3 panels for each façade).

The building features a one-way RC frame structure, arranged along three alignments in the longitudinal direction. The frames all consist of columns (30x30) cm^2 and beams in slab thickness (h=24 cm). It was supposed to be located in a high seismicity zone of the Italian territory (a_g=0.261 g, F_0=2.364, T_c^*=0.346 s, S=1.153).

A numerical model was developed for the building on which a nonlinear static analysis was performed by assigning flexural and shear plastic hinges to beams and columns, considering P-M-M interaction for columns.

The results, reported in Fig. 5, show the building's poor performance in terms of stiffness and strength, particularly for the Y-direction, but without exhibiting brittle failure. The minimum safety index at LSLS results 0.57 for the Y direction.

From the MDOF capacity curves of the existing building, referred to modal distribution, input data were extrapolated for the retrofit design adopting a D-DBD approach [24], from which the design stiffness ($k_{e,2}$) and strength (F_{y2}) for the exoskeleton are finally derived, as shown in Tab. 1. This data will then be used for the design and comparison of three different exoskeleton solutions, all conceived with adaptive behaviour at LSLS:

1. Shell
2. Coupled walls
   2.1. Along the entire façade
   2.2. By connecting the walls in pairs (X direction)
3. Single walls

It is worth noting that all the schemes described above consider the adoption of balloon-type CLT panels,

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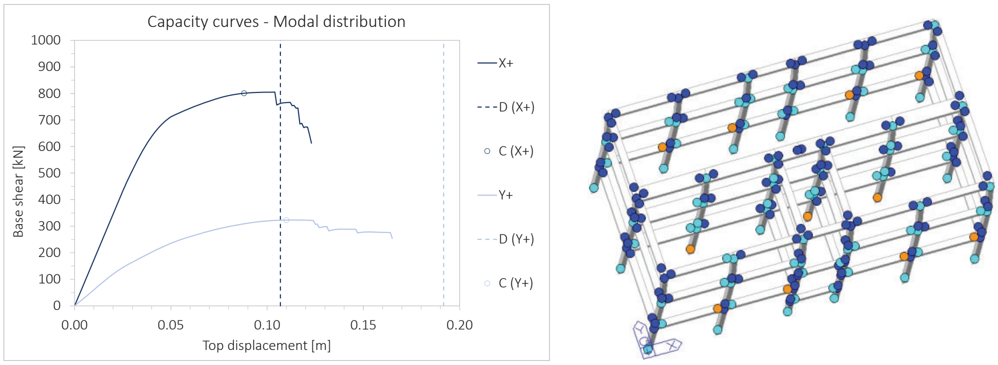

Figure 5. Capacity curves for the as-is building (D=displacement demand, C=displacement capacity at LSLS) with plastic hinges activation at the incipient collapse in X direction (Blue: elastic; Light blue: yielding rotation; Orange: ultimate rotation).

equipped with hold-downs and concentric unbonded prestressed tendons.

Table 1: Parameters considered for the design of the exoskeleton.

Input parameters for the as-is building (1)				
Reference direction			X	Y
Participating mass	m_1	(kN)	5556	5211
Yielding strength	F_{y1}	(kN)	753	305
Yielding displacement	Δ_{y1}	(m)	0.044	0.060
Ultimate displacement	Δ_{u1}	(m)	0.123	0.124
Elastic damping	$\xi_{el,1}$	(%)	5	5
Design parameters at LSLS				
Target displacement	Δ_d	(m)	0.044	0.047
Participating mass	m_2	(kN)	267	250
Recentring ratio	λ_2		1.15	1.25
Damping factor	η		0.80	0.80
Output parameters for the exoskeleton (2)				
Effective stiffness	$k_{e,2}$	(kN/m)	36'758	39'918
Stiffness ratio	$k_{e,2}/k_1$		2.14	7.80
Yielding strength	F_{y2}	(kN)	1613	1856
Strength ratio	F_{y2}/F_{y1}		2.14	6.09
Effective damping	$\xi_{eff,2}$	(%)	13	11

It is worth noting that by adopting a damping correction factor (η) less than 1, the maximum expected accelerations for the retrofitted building can be reduced by taking advantage of the adaptive behaviour of the exoskeleton.

The recentring ratio (λ_2) for the exoskeleton, required for the evaluation of the effective damping ($\xi_{eff,2}$), was defined in accordance with [25], as the ratio between the elastic ($M_{El,2}$) and the dissipative ($M_{Diss,2}$) contribution provided at LSLS:

$$\lambda_2 = M_{El,2} / M_{Diss,2} \geq 1.15 \tag{4}$$

The ratio between the dissipative and the total resisting capacity (β_{1+2}) was also evaluated considering the resisting contribution offered by the existing building (M_1), which for the target displacement results in the elastic range:

$$\beta_{1+2} = M_{Diss,2} / (M_{El,2} + M_1) \leq 0.4 \tag{5}$$

With the yielding strength obtained (F_{y2}), it is possible to design the CLT panels and connections of the exoskeleton according to the selected static scheme. For designing purposes, a class C24 timber was considered for the CLT panels, a pair of hold-downs for each panel with a tensile strength of 200 kN [12] placed at 20 cm from the edges, and for post-tensioning purposes, a total axial stressing action, under seismic conditions, equal to 30% of the panel's compressive strength was considered. Dissipative behaviour at LSLS is attributed to hold-downs (C4) for the single wall solution, and to couplers (C1, C2) for the other solutions. In that cases, hysteretic connections arranged along the vertical interfaces between existing openings, positioned at the centreline to ensure transfer of shear actions only, were considered [12]. The results obtained from the design are evaluated according to (1), (2), (3) and then shown in Tab. 2.

After dimensioning the exoskeleton, numerical modelling of the shell solution is carried out (Fig. 6). To obtain a model that is easily implementable and adaptable to the different structural schemes CLT panels (E1, E2) are schematized as Timoshenko beams, with a rigid base (E3) supported by distributed springs (F1) that simulate the panel-to-foundation interaction. The exoskeleton foundation (E5) is also modelled as a beam on elastic soil (F2), continuous along the perimeter of the building, with springs at each corner to simulate the axial contribution of micropyles (C5). All the exoskeleton connections (C1, C2, C3, C4) are modelled with lumped general link elements, with calibrated stiffness and strength based on the actual connections to be adopted. The p-t tendons (E4) are introduced as truss elements spanning from the top node of the CLT panels to the respective node on the RC foundation, loaded with the pretension load obtained

Table 2: Design parameters obtained for different exoskeleton solutions.

Structural scheme			**1**		**2.1**		**2.2**	**3**	
Reference direction			X	Y	X	Y	X	X	Y
CLT thickness	t	(mm)	100	180	100	180	100	230	350
Prestress load	$N_{p\text{-}t}$	(kN)	382	1141	382	1141	382	1117	2435
Recentring ratio	β_{1+2}		0.32	0.39	0.32	0.39	0.32	0.20	0.14
Lever arm	L (d_{1n})	(m)	19.2	10.3	17.2	7.8	3.5		
Couplers strength	F_{c1}	(kN)	140	286	156	378	255		
	F_{c2}	(kN)	286						

in the design phase. The model described can easily be adapted to the different structural schemes analysed simply by changing the stiffness of panel's connections (C1, C2). For example, when $k_{C1}=k_{C2}=0$, a single wall exoskeleton can be obtained.

To evaluate the design process previously described nonlinear static analysis are carried out on different exoskeleton configurations (M1, M2.1, M2.2, M3), considering the existing building on pinned columns. In models M2.1, M2.2 and M3 two alternative versions are considered:

A. Walls designed with the same panel thickness (t) and connections strength (F_{c1}) as for the shell solution, that implies lower performance;

B. Walls designed to be iso-performance with the shell solution, increasing panel thickness (t) or connections strength (F_{c1}) as reported in Tab. 2.

The capacity curves of all the numerical models are compared in Fig. 7, the graphs also show the existing building in the as-is condition (M0), the design force considered for shell exoskeleton (F_{y2}) and the LSLS target displacement imposed (Δ_d).

From the graphs it is possible to observe that all iso-performance curves reach a base shear comparable to the imposed design force although with different initial stiffnesses. The shell (M1) and coupled wall (M2.1, M2.2) solutions exhibit trilinear behaviour, with the first branch characterized by high stiffness until the

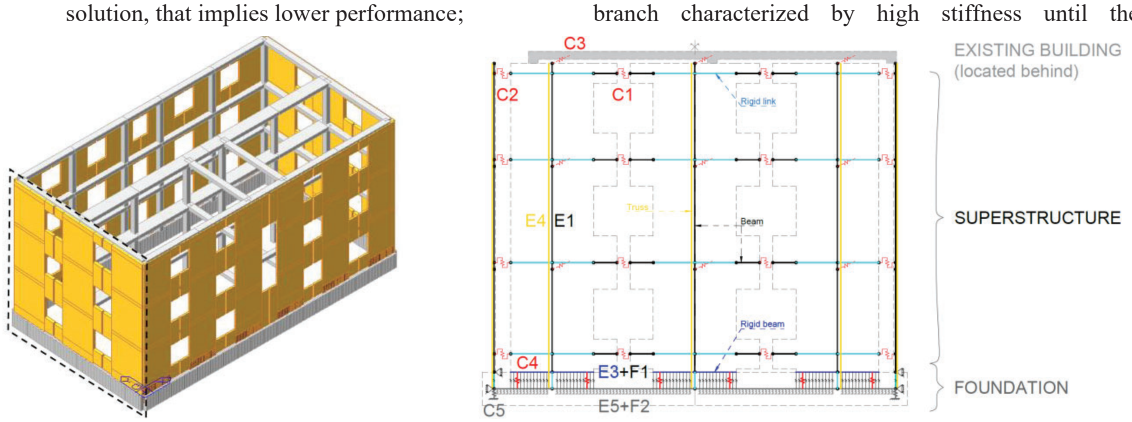

Figure 6. 3D numerical model of the retrofitted building and schematization of modelling choices for the shell exoskeleton.

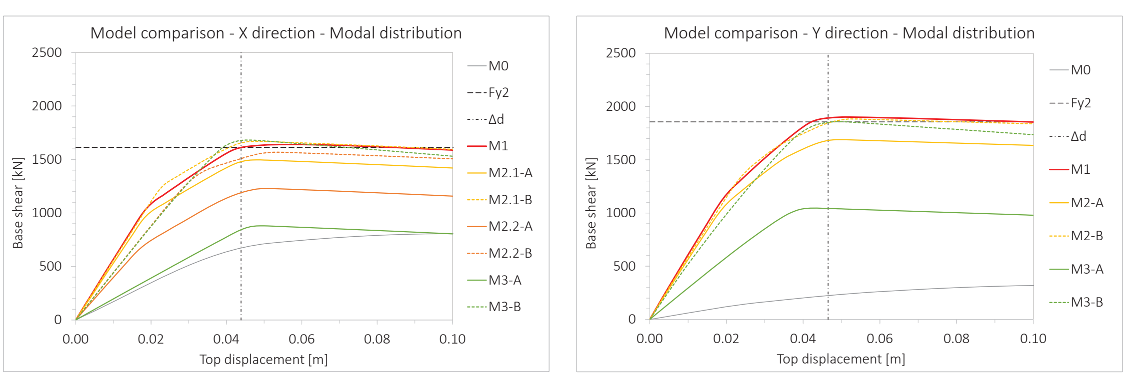

Figure 7. Comparison between capacity curves of the exoskeleton solutions for X (left) and Y (right) direction.

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dissipative connections are activated, which initiates the second branch in which the slope of the curves is the same as in M3-A, as the exoskeleton undergoes a downgrade to the single wall scheme. The end of the second branch of the curve coincides with the plasticization of all panel's connections and with the target displacement imposed at LSLS. In models 2-A and 3-A, it can be observed the progressive reduction in stiffness and strength offered by the exoskeleton as it moves from shell to single wall scheme, considering the same panel geometry and connections strength.

The model of the shell exoskeleton (M1) is subsequently analysed by also considering the resistant contribution of the existing building. Fig. 8 shows the comparison between the pre- and post-intervention capacity curves for the longitudinal direction, with the critical points for each curve related to the activation of the plastic hinges. There is a marked difference between the curves in terms of stiffness, strength and ductility. In fact, the introduction of the exoskeleton allows regularizing the deformation of the existing building by activating more plastic hinges between the beams, which leads to an increase in displacement capacity. Still evident is the trilinear behaviour guaranteed by the exoskeleton in which the first elements to achieve plasticization are the connections between panels (A), followed by the hold-downs (B) and then all the columns of the existing building at the base section (C). The resulting collapse mechanism sees plasticization of the beams at all floors and the columns at the ground floor (D), ensuring high ductility. From the capacity curve of the retrofitted building it can be deduced that, if the earthquake-induced displacement demand is less than the displacement corresponding to point B, the building will be able to

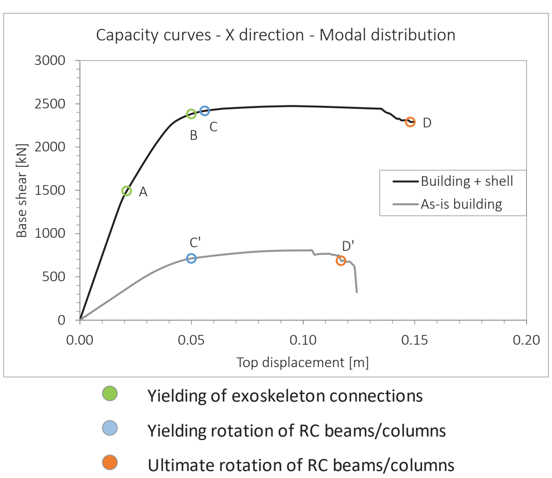

Figure 8. Comparison of the capacity curves in the longitudinal direction for the building in the as-is condition and the retrofitted building with shell exoskeleton. Significant points related to the activation of plastic hinges are plotted in the graphs.

exhibit self-centring behaviour by taking advantage of the stabilizing contribution offered by the base connections, the p-t tendons and the existing RC structures.

It is worth noting that the proposed example refers to a regular building and aims to validate the advanced design criteria highlighting the potential benefits of CLT shell exoskeletons. Further sensitivity analyses should be performed to assess the limits of applicability of the solution depending on the size and regularity of the reference building, also targeting geometric limitations dictated by the maximum allowable size of CLT panels.

5 – CONCLUDING REMARKS

In renovating the existing building stock, a design approach that prioritizes sustainability and resilience throughout the building life cycle is essential. Re-engineering timber dry construction techniques from an LCT perspective may be quite promising for achieving these goals, as CLT panels offer advantages for prefabricated, lightweight, efficient structures, applicable to deep renovation of existing buildings with exoskeleton solutions. These external structural systems reduce interference with building use and, when designed according to LCT approach, enhance performance while mitigating seismic impacts. Comparative analysis of timber exoskeletons applied to a post-World War II 3-story RC building highlights the shell solution as the most effective, offering superior global strength and stiffness while reducing demand on individual connections. Ongoing research aims to further evaluate the limits of this approach based on building geometry and structural regularity. These findings highlight the significant potential of timber exoskeletons for the integrated and sustainable renovation of existing buildings and open up many research topics to be explored.

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