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ENHANCING THE RESILIENCE OF EXISTING BUILDINGS USING LOW-DAMAGE EXOSKELETONS: A PROOF OF CONCEPT THROUGH A MULTI-HAZARD RISK ASSESSMENT PROCEDURE

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Abstract

The building sector, responsible for 35% of global energy use and 38% of CO_2 emissions, plays a key role in mitigating climate change. Underperforming building envelopes cause high energy consumption and expose occupants to unsafe climate extremes. Additionally, in seismic- and flood-prone areas, outdated buildings lack resilience, posing severe economic and human risks. Renovation must thus improve energy efficiency, multi-hazard resilience and sustainability through low-carbon and resource-efficient solutions. This study explores a holistic renovation strategy using timber low-damage exoskeletons to enhance seismic resilience while supporting energy-efficient facades. The design also integrates flood-resistant materials and dry flood-proofing measures. A multi-hazard assessment on a case study evaluates resilience improvements using seismic, energy, and flood simulations. The findings highlight the effectiveness of the strategy for building renovation, with an overall reduction of about 50% in combined losses.

Keywords: Integrated (seismic/energy) rehabilitation, Low-damage technologies, Exoskeletons, Multi-Hazard approaches, Flood risk, Sustainable renovation.

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1 INTRODUCTION

The current global emergency related to climate change requires an urgent effort to reduce CO_2 emissions. Accounting for 35% of global energy consumption and 38% of CO_2 emissions, the building sector could offer an important contribution in facing such an emergency [1]. Such high values are mostly related to ageing and underperforming buildings, which were erected before current energy regulations. Additionally, other than being "energy-sinks", these buildings could represent a growing threat to inhabitants' health as climate-related extremes, such as heat waves become more frequent. This justifies the significant effort that researchers worldwide are undertaking to improve the energy efficiency of existing buildings, ultimately aligning with the ambitious goals of the *Paris Agreement* [2], the *European Green Deal*, and the associated *Renovation Wave for Europe* [3]. In parallel, in countries prone to seismic and flood risk, where existing buildings have been erected prior to modern seismic codes and without adequate measures to mitigate the hydraulic hazards, the built environment is highly vulnerable. Such vulnerabilities pose an economic risk and a risk to human lives. Efficient and comprehensive renovation strategies should therefore be conceived by embracing multiple hazards (rather than single domains), thus effectively enhancing the community's resilience and energy efficiency. Finally, improving resilience should not be at the expense of environmental sustainability, consequently, the built environment should be renovated in a low-carbon manner by promoting resource-efficient design approaches and the use of eco-friendly and reusable materials and components. This paper proposes an integrated rehabilitation solution that can be implemented entirely from outside the building, thus limiting occupant disruption and building downtime. This aspect is of paramount importance because owners' disruption is a crucial indicator in Multi-Criteria Decision-Making (MCDM) approaches for selecting the best renovation alternative [4]. Building on the considerations above, researchers are currently focusing on developing alternative exoskeleton solutions (that can be implemented from outside) for the integrated renovation of the existing building stock [5], also focusing on timber-based (i.e., eco-friendly) solutions [6,7].

This paper aims to investigate, in a multi-hazard approach, the efficiency of a holistic renovation strategy based on low-damage timber-based exoskeletons. The seismic-resistant low-damage technology adopted in this study is the Prestressed-Laminated (Pres-Lam) timber technology [8–10], developed at the University of Canterbury, and widely used in new resilient buildings. The exoskeleton provides additional strength and stiffness to the existing building, thus allowing for structural retrofit and enhancing seismic resilience. At the same time, it provides support for a high-performance facade system, promoting energy upgrades and architectural restyling. As a result, the proposed exoskeleton can be considered as a multi-performance second skin of the existing building. Moreover, considering the hydraulic risk, such an exoskeleton should be designed, at least under the flood level, using flood-resisting materials and adopting floodproofing measures (e.g., waterproofing paint and coatings). Moreover, a multi-hazard assessment procedure is adopted to prove the enhanced resilience of buildings retrofitted using the abovementioned exoskeleton solution. More specifically, this work demonstrates the potential of the exoskeleton in a multi-hazard perspective through an application on a case-study building in Italy. The overall performance of the as-built and retrofitted configurations is assessed by conducting seismic, energy, and flood simulations. The results of the analyses aim to define the economic losses, in terms of combined Expected Annual Losses (EAL), related to earthquakes (EAL_S), energy consumption (EAL_E), and floods (EAL_F). The paper is structured as follows: §2 presents the case study building and the methodology implemented; in §3, the results of the seismic, energy, and flood simulations are presented, and the achieved reduction of the overall losses by implementing the proposed intervention is discussed. Finally, §4 provides conclusions and suggestions for future developments.

1.1 As-Built configuration

The structural characteristics of the case study considered in this study are as follows: A 4-story existing Reinforced Concrete (RC) infilled frame building designed for gravity loads only, thus disregarding any considerations related to "capacity design" and "hierarchy of strength" as prescribed by modern seismic codes. Consequently, the building is expected to be "seismic prone", since it reflects the main vulnerabilities observed in pre-code buildings [11]. The building is residential, with a 19.50 m x 10.05 m rectangular floor plan (Fig. 1a), the inter-story height is 3.10 m, and it is located in an Italian site featured by a medium seismic hazard. The concrete used in the building has a mean (50th percentile) cylinder compressive strength of 20 MPa, while reinforcing steel is featured by a mean yielding (f_y) and mean ultimate stress (f_u) equal to 430 MPa and 540 MPa, respectively. The acceleration and displacement spectra at the Life-Safety Limit-State (LSLS, with a return period of 475 years) are provided in Fig. 1b.

The energy performance characteristics of the as-built configuration are as follows: The vertical opaque envelope consists of 20 cm-thick infill panels with a U-value (thermal transmittance) equal to 1.17 W/m^{2}K, with a 15% window-to-wall ratio. Windows consist of single glazing in timber frames, resulting in a U-value of 4.90 W/m^{2}K. The roof consists of a slab (clay blocks with an RC topping) with two additional finishing layers, namely, a concrete screed and a flooring system. The U-value of the roof is equal to 3.67 W/m^{2}K. The building is located in climatic zone E (corresponding to a value for Heating Degree Days, HDD, between 2101 and 3000) [12]. Concerning flood risk, detailed information is provided in §3.3.

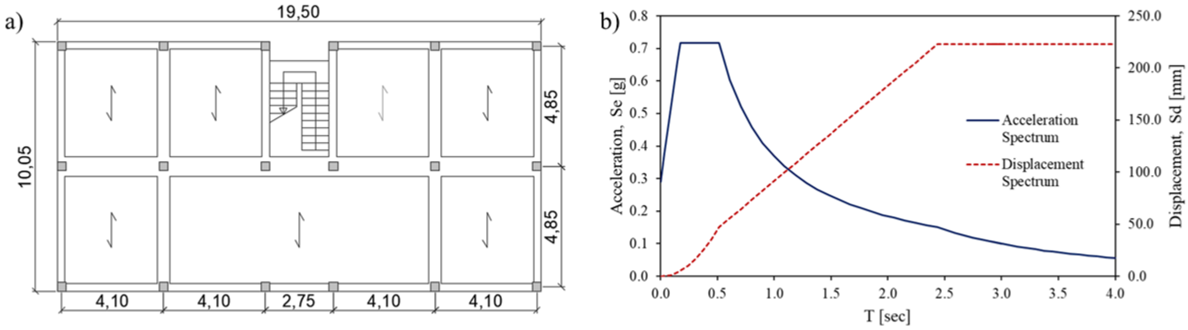

Figure 1. a) Plan view of the selected case study building. Columns are 35x35cm at the first two stories and 30x30cm at the last two, perimetral beams are 30x50 cm, the hidden beam in the longitudinal direction is 80x20cm, while hidden beams in the transversal direction are 50x20cm. b) acceleration and displacement spectra at the Life-Safety Limit-State (LSLS) for the site of interest (Peak Ground Acceleration, PGA = 0.291g, and Soil Class C).

1.2 The low-damage exoskeleton for the integrated renovation approach

The renovation approach presented in this study (Fig. 2) involves the implementation of a low-damage timber-based exoskeleton based on the Prestressed Laminated (Pres-Lam) technology developed at the University of Canterbury, New Zealand, in the 2000s [8–10]. This low-damage technology is based on jointed ductile connections between structural members, allowing for a distinctive rocking-&-dissipative mechanism at the interface between components (i.e., beam-to-column as in Fig. 2, column-to-foundation, and wall-to-foundation). The connections feature two types of reinforcement. The first consists of unbonded cable/bars designed to remain elastic and ensure the pre-existing gap (among members) closure at the end of shaking, while the second consists of external and replaceable "Plug&Play" dissipaters [13,14], ensuring energy dissipation capabilities. By combining in parallel such types of reinforcement, a "flag-shaped" hysteresis response [15] is obtained for the Pres-Lam system, ensuring both energy dissipation as well as the distinctive self-centering capability of the system, which prevents residual displacements.

In order to fully protect the structural exoskeleton from water (especially considering the flood risk considered in this study), specific measures should be considered. Specifically, protecting timber from floods requires coatings that enhance water resistance, durability, and resistance to microbial growth. To this end, waterproof paints such as epoxy coatings, polyurethane coatings, or acrylic latex paints, combined with sealants for maximum protection, must be implemented. Fully protecting structural members from flooding is crucial because damage to ground-floor columns would lead to the complete disassembly of the exoskeleton to replace the affected columns, leading to high repair costs. Similarly, at the ground floor, the wooden components of the facade (CLT panels and timber studs, refer below for further details) should be protected by implementing the waterproof measures discussed above.

In addition to water protection of timber components, flood adaptation strategies were incorporated based on FEMA P-259 (2012) guidelines. Specifically, dry floodproofing measures were implemented, including: 1) elevating critical equipment (e.g., boilers) above the forecasted inundation depth, and 2) deploying flood barriers to protect external doors and windows. The additional cost of these floodproofing measures was assumed to be negligible compared to the overall cost of the seismic and energy retrofit (Attems et al., 2019 [16]).

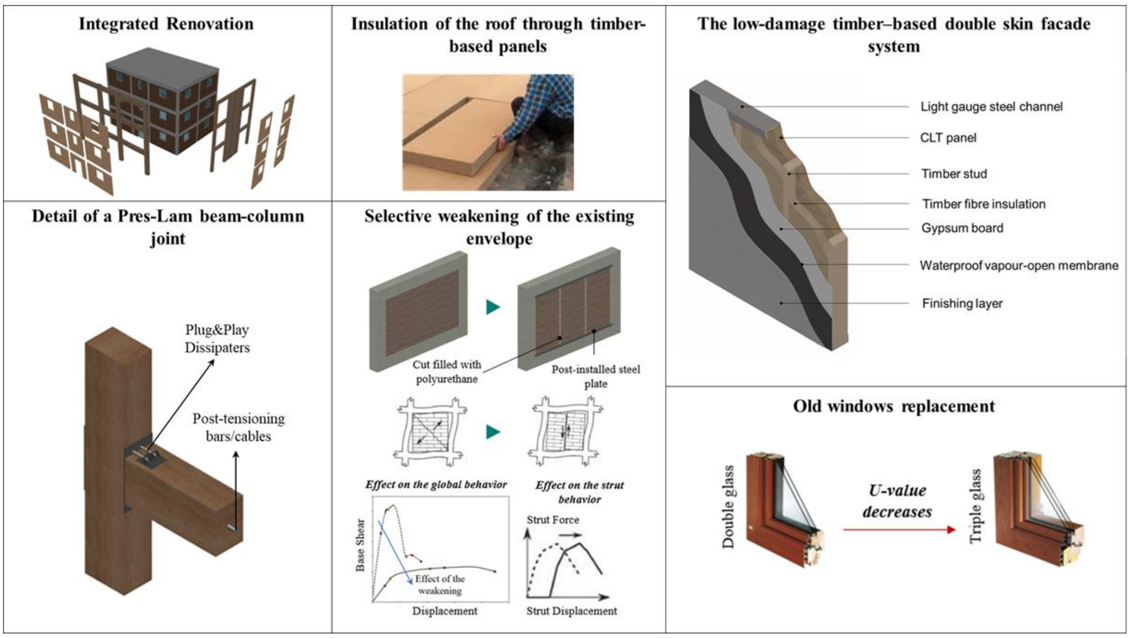

Figure 2. Schematic representation of the holistic rehabilitation intervention based on low-damage double-skin exoskeletons.

The connection between the as-built structure and the exoskeleton is provided by dowels specifically designed to allow for the shear transfer between the two structures.

Due to the vulnerability of the existing envelope, low-damage technologies are used to enhance seismic resilience and protect energy refurbishment investments. This involves increasing the in-plane capacity of masonry infill walls by making vertical and horizontal cuts, creating a system based on rocking panels for which it is possible to control the drift where the damage initiates [17], as illustrated in Fig. 2 ("*Selective weakening of existing envelopes*"). Further information related to this approach for enhancing the seismic resilience of existing masonry infills, also considering out-of-plane stability, can be found in [18].

Moreover, a timber-based low-damage double-skin facade system is infilled within the structural exoskeleton to promote energy refurbishment and architectural restyling. The proposed system follows a similar concept to that proposed by Tasligedik et al. (2015) [19] for timber-framed drywall partitions. For all the details related to the facade herein considered (Fig. 2), the reader can refer to [18].

Finally, the insulation of the roof is implemented through timber-based panels, and the replacement of existing windows is considered as well. The characteristics of windows, roof insulation panels, and the double-skin facade system layers have been defined by following the indication provided in DM 26/06 2015 [12] to achieve the target U-values.

1.3 Seismic design of the timber-based low-damage exoskeleton

The additional structural system (i.e., the exoskeleton) for the seismic retrofit of the considered building has been designed by following the Displacement-Based Retrofit (DBR) approach proposed by D'Amore & Pampanin (2025) [20] for RC exoskeletons in the form of frame systems. Such a procedure is an extension of the Direct Displacement-Based Design (DDBD) approach proposed in the past for designing new buildings [21]. The main scope of the procedure is preventing the as-built structure from reaching its failure displacement profile (e.g., at the LSLS), which can be defined through a detailed assessment procedure.

Since this work focuses on a timber exoskeleton, minor adjustments to the procedure mentioned above should be considered. More specifically, in the case of timber structures, the Serviceability Limit State (SLS) generally governs the size of members and the amount of post-tensioning. This verification at SLS provides a structural system with the required stiffness to protect non-structural components and the as-built structure in case of frequent events. After the verification at the SLS, a detailed design of connections can be carried out (at the LSLS) to meet the required seismic demand. Moreover, the re-centering ratio λ [15] was set to 1.50, to ensure the self-centering capabilities of the retrofitted system.

1.4 Seismic modeling approach and performance assessment

Seismic analyses were implemented through 3D models using the SAP2000 software [22]. A lumped plasticity approach was adopted for the as-built structure. Specifically, structural members were modelled through frame elements with plastic hinges located at their end sections. Plastic hinge behavior was modelled through moment-curvature relationships, and the hinge length was defined according to Priestley et al. (2007) [21]. Shear and combined shear/flexural failures were accounted for by following the New Zealand guidelines for seismic assessment of existing buildings [23]. The hysteretic behavior was implemented by means of the Pivot model available in SAP2000, as indicated in previous research (e.g., Molitierno et al., 2023 [24]). Beam-column joints were modelled by using a system of rigid links and rotational springs [25]. The moment-shear deformation relationship of joints was derived as outlined in [23]. The Pivot model was also adopted for beam-column joints to capture their hysteretic behavior. More specifically, the parameters of the hysteretic model were calibrated by modelling in SAP2000 beam-column joints tested in past experiments [26], and benchmarking the results of the analyses with experimental data. The masonry infills were considered as a single strut, where each infill panel is modelled using two links working only in compression. The tri-linear shear-displacement relationship proposed by Panagiotakos & Fardis [27] was used to model the response of each infill. The hysteretic behavior, as in the other above-mentioned elements, was modelled by using the Pivot model [24].

The numerical model of the retrofitted configuration consisted of the exoskeleton connected in parallel to the as-built structure through rigid links representative of the specifically designed dowelled connections to ensure shear transfer between the two structures. The exoskeleton structure itself consists of non-linear rotational springs working in parallel at the end sections of members, thereby representing the distinctive rocking-&-dissipative mechanism at the interface between structural components, as suggested by Pampanin et al. (2001) [28]. Moreover, a rotational spring was included within the system of rigid links, representing the beam-column joint, for capturing the timber joint shear stiffness [29]. Moreover, in the retrofitted configuration, masonry infills were excluded from the model due to the introduction of lateral gaps (selective weakening of infills) that prevent the development of strut action. A schematic representation of the modelling approach is shown in Fig. 3.

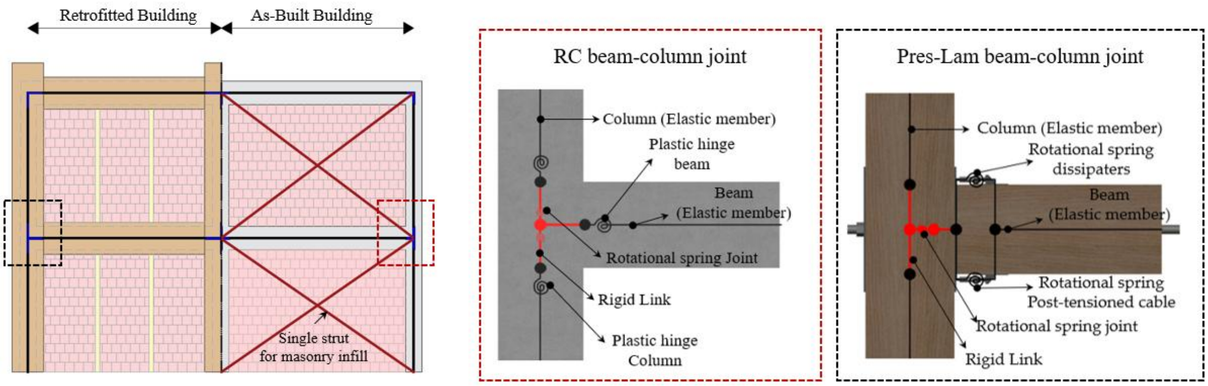

Figure 3. Lumped plasticity modelling approach for the implementation of the numerical models in both the as-built and retrofitted configurations.

Using the results of non-linear static (push-over) analyses, the seismic performance of the case study in the as-built and retrofitted configurations was defined by following the "*Italian Guidelines for Seismic Risk Classification of Constructions*" [30]. More specifically, this approach requires the definition of a Safety Index (i.e., IS-V defined as the ratio between the capacity and the demand at the LSLS, and analogous to the %NBS defined in [23]), and an Economic Index related to the Expected Annual Losses (EAL_S, or PAM in Italian).

1.5 Energy modeling and analyses

The energy performance of the building, both in the as-built and in the retrofitted configuration, was assessed from numerical models in the Grasshopper environment and performing the energy analyses through EnergyPlus [31]. Detailed information related to the definition of the numerical model, of material properties to ensure the required U-values, of design requirements adopted for indoor comfort, and other essential parameters required for performing energy analyses, can be found in previous works of the authors (e.g., [18,32]). Energy costs were defined from the analyses according to the prices of electricity (0.295 €/kWh) and gas (0.129 €/kWh) provided by *Eurostat*[1] for Italy. These prices were used to determine the Expected Annual Losses related to energy consumption (EAL_E).

1.6 Flood modeling and analyses

A flood risk assessment was conducted to evaluate direct losses, i.e., defined as the ratio of damage impact to the total replacement cost of the building, due to pluvial flooding. This

[1] https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20231026-1

assessment was carried out by integrating three key components: hazard, exposure, and vulnerability.

The hazard analysis was performed at the building's location to estimate flood intensity measures such as depth, velocity, and duration. However, in this study, only flood depth was considered, while velocity and duration were excluded. The outcome of the flood hazard analysis was a hazard curve, representing the intensity of the event based on its return period.

For the exposure assessment, key factors such as the building location, occupancy type, and the positioning of critical components on the ground floor were analysed, following the procedure outlined by Nofal et al. (2020) [33]. Using Nofal's framework, a damage function, i.e., indicating the level of damage for a given flood intensity, was developed and integrated with the hazard and exposure assessments to estimate the expected annual losses for both the as-built structure and the retrofit solution. Consequences implemented in the procedure are taken from FEMA P-58 [34] or literature (e.g., Cardone & Perrone 2015 [35]).

2 RESULTS AND DISCUSSION

2.1 Seismic performance

Seismic performance was evaluated through non-linear static (push-over) analyses. For brevity, only the results related to the longitudinal direction are presented here. First, a pushover analysis was implemented for the RC infilled frame building in the as-built configuration (Fig. 4a). In this case, the failure mechanism is governed by shear failures in columns due to the interaction with the masonry infills. More specifically, since the numerical models have been implemented by using a single-strut approach (i.e., neglecting the local interaction between structural and non-structural components), an a-posteriori evaluation was conducted to assess such an interaction. Following an approach analogous to that presented in Di Trapani et al. (2023) [36], it was possible to consider the shear acting on the column as the sum of the drift-related shear acting on the frame, and the additional shear demand induced by the interaction with the infill. The latter can be considered as a portion of the horizontal component of the force acting on the strut, and more specifically, only the rate transmitted to the column through horizontal normal stresses, i.e. excluding the portion transferred through shear stresses between the top of the infill and the intrados of the beam. On the other hand, the shear capacity of the columns was evaluated using the model available in the NZSEE guidelines [23], and such a capacity was compared to the demand to define the step of the analysis where the failure occurred.

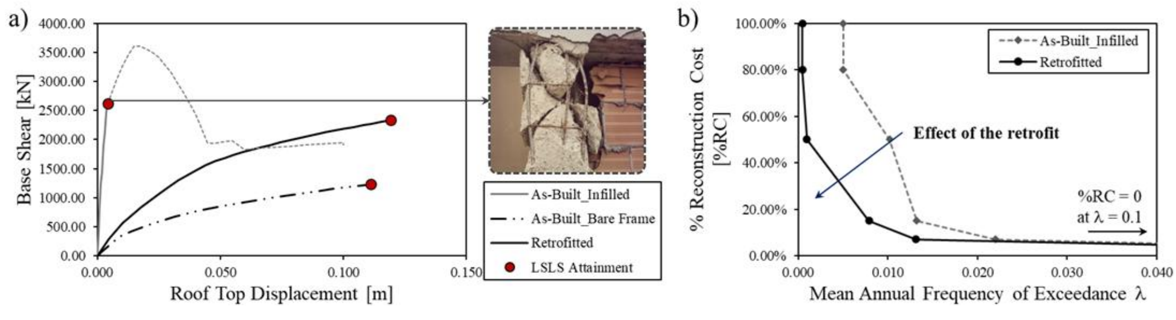

Figure 4. a) Pushover analyses for the various cases, and b) EAL_S curves for the as-built and retrofitted configurations

A second analysis was then carried out by neglecting the effect of the infills, thus reflecting the effect of the selective weakening approach outlined in §2.2. The results (Fig. 4a), indicate that

the shear failure in columns is prevented, and the as-built structure, with selective weakening of masonry infills, presents a more desirable ductile behavior, even if a significant reduction of strength and stiffness is observed. Finally, Fig. 4a also shows the results of the pushover analysis of the retrofitted configuration. The effect of the low-damage exoskeleton (consisting of both glulam timber GL30C beams and columns with dimensions 68 cm in height and 32 cm in width) is clear both in terms of improvement in strength and stiffness. Moreover, the retrofitted solution achieves an increase in the maximum displacement, as a result of the added stiffness that contributes to redistributing inelasticity along the height and preventing damage concentration in only a few zones, as observed in past research (e.g., [20]).
Building on the results of the analyses mentioned above, it was possible to assess the IS-V value both in the as-built and retrofitted configurations. Specifically, the as-built structure scores 52% IS-V, while for the retrofitted building, the IS-V achieves 139%, thereby demonstrating the effectiveness of the exoskeleton solutions in significantly improving seismic safety. Moreover, the EAL_S have been evaluated, and the associated curves are presented in Fig. 4b. More specifically, the expected losses decrease from 1.31% in the as-built configuration to 0.66% in the retrofitted one. Once again, the economic metric supports the effectiveness of the proposed solution, which is indeed able to halve the EAL_S. Table 1 summarizes the results both in terms of IS-V as well as of EAL_S.

Configuration	IS-V	EAL_S
As-Built	52%	1.31%
Retrofitted	139%	0.66%

Table 1: Results in terms of Safety-Index (IS-V) and expected seismic losses (EAL_S) for the as-built and retrofitted (implementing the low-damage exoskeleton) configurations.

Finally, it is worth mentioning that while the results highlight a drastic reduction of the EAL_S in the retrofitted configuration, the 0.66% value is expected to be conservative, and the reduction of real-world EAL is expected to be even more significant. This underestimation is related to the consequence model adopted in this study, which is based on the actual repair costs observed in the aftermath of the 2009 L'Aquila (Italy) earthquake (*White Book*, [37]). Such a model is unable to capture the advantages of the Pres-Lam technology (i.e., reduced cost/time for repair activities when compared to traditional building technologies, as well as the beneficial effect of reduced/negligible residual displacement). Nevertheless, it is worth mentioning that the framework for evaluating the combined losses (i.e., EAL_S, EAL_E, and EAL_F) remains valid regardless of the approach adopted for assessing the losses themselves. In order to capture the advantages of adopting a low-damage structural exoskeleton relying on the Pres-Lam technology, the authors are currently carrying out research within the Horizon Europe MULTICARE[2] project. Specifically, through a synergic collaboration with industrial partners, consequence models are being developed to represent a more refined component-based loss assessment procedure (e.g., similar to that outlined in the FEMA P-58 [34]).

2.2 Energy performance

Dynamic energy simulations were performed to predict the expected energy losses (EAL_E) for the considered case study in both the as-built and retrofitted configurations. The results of the analysis, provided in terms of hourly energy consumption for the loads considered (i.e., heating, cooling, hot water production, electric equipment, and lighting), have been elaborated to define

[2] https://multicare-project.eu/

the energy costs and related losses. The results in terms of energy consumption, costs, and expected losses are reported in Table 2 for both configurations (i.e., as-built and retrofitted).

Configuration	Consumption [kWh/m^2]	Cost [k€]	EAL_E [%]
As-Built	230.52	26.33	2.95%
Retrofitted	97.93	14.25	1.60%

Table 2: Results of the energy simulations for the as-built and retrofitted configurations in terms of energy consumption, costs, and expected annual losses (EAL_E).

The results clearly highlight the benefits provided by the additional façade skin system, together with the roof insulation and the replacement of windows, in drastically reducing the EAL_E, which moves from 2.95% to 1.60%. In any case, it is worth stressing that such a reduction is only related to the improvement of the characteristics of the building envelope (i.e., installation of double-skin facade system, insulation of the roof, and replacement of old windows). Further reduced values of the losses could be obtained by mounting energy generation technologies such as solar and photovoltaic panels on the exoskeleton.

2.3 Loss assessment for flood

A flood risk assessment was conducted for both the as-built and retrofitted solutions. This study utilizes a generic mean flood hazard curve, shown in Fig. 5a, which is assumed to be representative of the building's location. To determine if the building is located in a floodplain (i.e., areas subjected to inundation from floodwater), the flood depth at a 100-year return period is typically assessed (FEMA 551). This represents the one-percent-annual-chance flood, also referred to as the "base flood". The mean water depth at a 100-year return period is equal to 0.57 m, and this value should be considered the base flood elevation in order to protect the building from flooding.

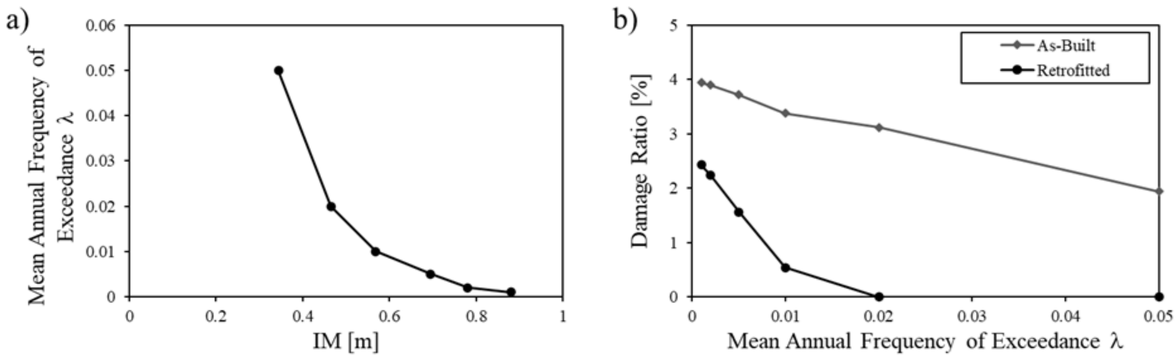

Figure 5. a) Mean hazard curve, and b) EALF curves for the as-built and retrofitted configurations.

Results for Expected Annual Losses from pluvial flooding (EAL_F) and repair costs are presented in Fig. 5b. Overall, direct losses are lower than those recorded in the seismic and energy risk assessments, as pluvial flooding of this magnitude only affects the ground floor. However, as summarized in Table 3, dry flood adaptation strategies prove highly effective, significantly reducing losses from 0.14% to 0.02%. Additionally, their cost impact is negligible compared to the overall retrofit expenses.

Configuration	EAL_F
As-Built	0.15%
Retrofitted	0.02%

Table 3: Results of the flood risk assessment for the as-built and retrofitted configurations in terms of damage ratio (EAL_F).

2.4 Results of the multi-hazard assessment procedure for evaluating the benefit of the exoskeleton solution

The benefits of implementing the integrated renovation strategy (addressing seismic/flood risk and energy efficiency) in a multi-hazard approach are assessed by determining the performance of the case-study building in both the pre-intervention and renovated configurations using combined losses (EAL_C) as a metric. The combined losses are the sum total of the expected losses derived from seismic (EAL_S), energy (EAL_E), and flood simulations (EAL_F). The results are presented in Fig.6 and Table 4.

Configuration	EAL_S [%]	EAL_E [%]	EAL_F [%]	EAL_C [%]	% Reduction EAL_C
As-Built	1.31%	2.95%	0.15%	4.41%	---
Retrofitted	0.66%	1.60%	0.02%	2.28%	-48.30%

Table 4: Results in terms of combined expected annual losses (EAL_C) for the as-built and retrofitted configurations, considering all the domains included in this study (i.e., seismic EAL_S, energetic EAL_E, and flood EAL_F).

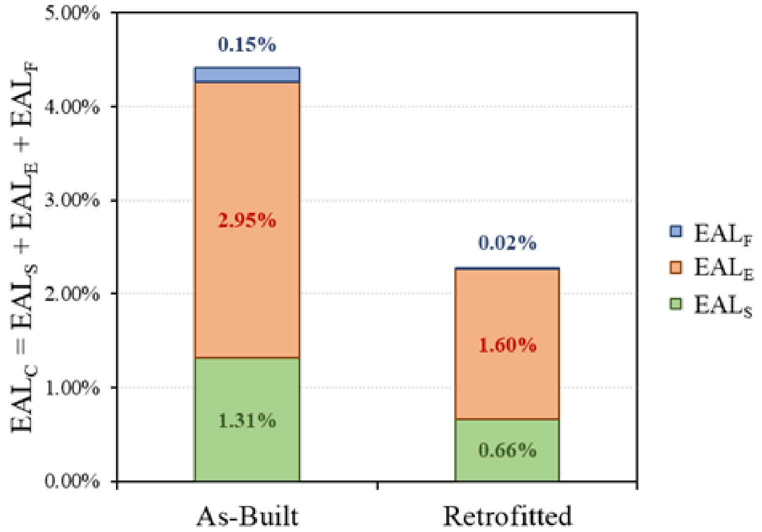

Figure 6. Results in terms of combined losses (EAL_C) for the as-built and retrofitted configurations.

Specifically, the EAL_C value decreases from 4.41% to 2.28%, corresponding to a percentage reduction of the overall losses equal to 48.30%, thus further highlighting the advantages of the proposed integrated intervention in a multi-hazard approach. In any case, it is worth stressing that even if the measures implemented for reducing flood risk allow for a drastic reduction of EAL_F, these values are considerably lower when compared to those derived from seismic and energy simulations. This aspect is mainly related to the fact that unlike the losses from seismic and energy risks, the flood risk affects only the ground floor of the building (i.e., damage is limited to such floor).

3 CONCLUSIONS

This paper presented a strategy based on an eco-friendly timber-based low-damage exoskeleton solution for the integrated renovation of the existing building stock in a multi-hazard perspective, thus considering seismic and flood risk, along with energy efficiency. More specifically, the structural exoskeleton proposed for the seismic retrofit, relies on the Prestressed-Laminated (Pres-Lam) timber technology and is equipped with high- and multi-performance low-damage facade systems promoting energy refurbishment and architectural restyling. Moreover, specific measures have been implemented regarding the hydraulic risk induced by flood (e.g., elevating critical equipment, such as boilers, above the forecasted inundation depth, and deploying flood barriers to protect external doors and windows).

The effectiveness of the solution has been proved through an illustrative case study application on an existing Reinforced Concrete (RC) infilled frame building. Specifically, seismic, energy, and flood simulations have been conducted to assess the expected annual losses (EAL) related to the domains herein considered. Finally, the combined losses (EAL_C, derived by summing those obtained from single domains) have been used as a metric to assess the benefits of the proposed strategy. Specifically, EAL_C is equal to 4.41% in the as-built configuration and reduced to 2.28% in the retrofitted one. This result proves the effectiveness of the proposed strategy in drastically decreasing the overall losses (which are reduced by 50%) and promoting an efficient possibility to move towards a more energy-efficient and resilient built environment from a multi-hazard perspective.

4 ACKNOWLEDGEMENTS

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