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EXTERNAL TIMBER-BASED LOW-DAMAGE EXOSKELETON SYSTEMS FOR ENHANCED STRUCTURAL SAFETY AND ENERGY EFFICIENCY

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Abstract: *The European building stock, mostly built post-World War II with no regard to seismic design and energy efficiency principles, is facing significant safety and sustainability challenges. The seismic vulnerability of existing buildings has been further confirmed by recent earthquake disasters, such as L'Aquila 2009, Centre Italy 2016, Turkey & Syria 2023, whereas the energy inefficiency is underscored by high energy consumption rates. An unprecedented effort is therefore required to increase seismic safety while achieving energy savings and decarbonization targets to meet the ambitious goals of the European Green Deal. Although several technical solutions are available in separate engineering domains, it is essential to adopt integrated renovation strategies (i.e., structural and energy efficient), especially when dealing with buildings located in zones with moderate-to-high seismicity.*

This work explores the application of exoskeleton-type solutions for integrated building renovation. Specifically, external load bearing systems consisting of low-damage timber-based structural members (the so-called Pres-Lam technology), that upgrade the seismic performance by reinforcing existing building. Such a solution is particularly attractive because the renovation interventions are entirely executed from outside the building, thereby reducing occupant disruption and avoiding relocation of inhabitants. This aspect is crucial in motivating owners to choose a combined low-invasive renovation that goes beyond simple energy retrofitting and improves the resilience of the energy upgrades, which on their own could become ineffective after future earthquakes. The proposed exoskeleton system has a dual role of operating as the support for a high-multi-performance "double-skin" facade system that improves the seismic resilience of the existing building and enhances its energy efficiency, thereby proving a holistic renovation.

The main goal of this work is to prove the effectiveness of the proposed integrated renovation strategy through an illustrative case study. The overall performance of both the as built/retrofitted structures is assessed by means of seismic and energy analyses. Building on such results, a loss assessment procedure is implemented to quantify the overall economic and environmental impact in the building lifespan. It is found that the proposed strategy enhances the holistic performance of the building with a 54% reduction of the economic losses.

1. Introduction

Recent devastating earthquakes occurred worldwide have further highlighted the extreme vulnerability of buildings built before the enforcement of modern seismic codes. Furthermore, 42% of non-residential and 38% of residential existing buildings exhibit high energy consumptions as they have been built before the introduction of modern energy regulations. Consequently, there is an urgent and unprecedented need to reduce both the seismic vulnerability and the energy consumptions to achieve a resilient and sustainable built environment. Specifically, the renovation of buildings could play an important role in the decarbonization of the

planet, as nowadays the building sector is responsible for 40% of energy consumptions and 36% of Green House Gas (GHG) emissions, Sajj (2016). By implementing such an unprecedented renovation strategy, in combination with the construction of nearly-zero energy buildings, it is possible to reduce the energy consumptions and the GHG emissions by 80% and 90%, respectively by 2050, Artola *et al.* (2016) thereby making a significant contribution to the ambitious and important goal of the *European Green Deal*. Furthermore, when dealing with seismic-prone countries, interventions aiming at enhancing the energy efficiency without improving the structural safety do not prevent the economic and human losses related to earthquakes. In addition, the carbon footprint related to reconstruction or post-earthquake repair activities should be considered. Specifically, Belleri and Marini (2016), pointed out that the ratio between the estimated expected annual embodied carbon related to seismic risk to the annual operational carbon dioxide, after thermal refurbishment, is about 10% and 87%, for the configurations with or without structural retrofit, respectively. These results further prove the importance of such an integrated intervention with respect to the only-energy one.

This justifies the recent research efforts that have been recently undertaken worldwide to prove the potential of integrated renovation strategy following a holistic design approach for improved seismic safety, energy efficiency, as well as architectural restyling of existing buildings. Furthermore, in the last decades, global external interventions are growing in interest due to the owners' reduced disruption. This aspect is particularly important as the disruption could lead the owners to opt for the light energy intervention only, which could be easily impaired even for low-to-moderate earthquakes, and completely lost, potentially together with the whole structure, for strong events. Over the past few years, several works have tackled the challenge of integrated renovation by exploring the combination of exoskeletons and "double skin" facade systems. Marini *et al.* (2017), proposed a holistic renovation approach based on the use of external steel exoskeletons and on the improvement of the building envelope using several strategies depending on the facade orientation. Manfredi and Masi (2018), investigated integrated interventions involving external infilled Reinforced Concrete (RC) frames connected to the as-built structure, thus enabling both the seismic strengthening and the energy upgrading. Margani *et al.* (2020) and Zanni *et al.* (2021) proved the efficiency of using Cross Laminated Timber (CLT) panels for the integrated renovation of RC framed buildings, considering the high strength and stiffness of this material together with its low thermal conductivity.

This paper investigates the benefits and attractiveness of external low-damage exoskeletons exploiting the Pres-Lam (Prestressed Laminated Timber) technology, which was developed in the early 2000's at the University of Canterbury (NZ), Palermo *et al.* (2005, 2006). Being the technology based on timber, it allows for the use of an efficient structural system built from sustainable and eco-friendly materials. The external exoskeleton serves the dual purpose of seismic strengthening and support for a high performing "double skin" facade system, enabling both for the energy refurbishment and the architectural restyling. Fig.1 presents a schematic representation of the proposed integrated intervention.

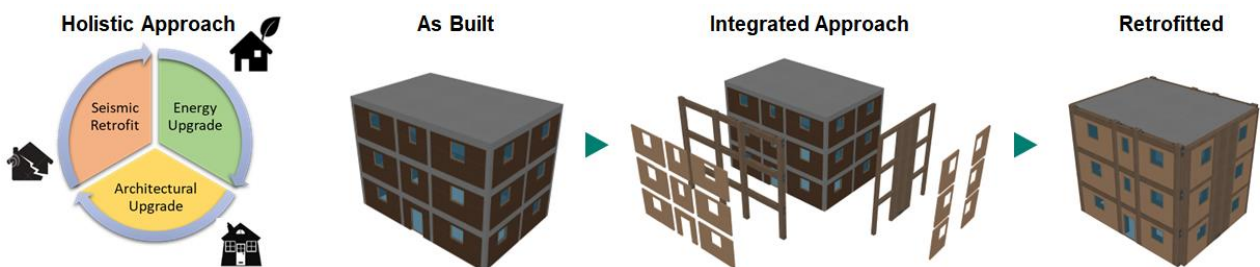


Figure 1. Schematic representation of the proposed integrated intervention.

The efficiency of the proposed technology is demonstrated for an existing RC building located in different climatic zones in Italy. These zones, featuring a high seismic hazard, encompass both warm and cold climate (i.e., Messina and L'Aquila), according to the classification provided by DM 26/06, (2015). After presenting the case-study building in the as-built configuration, the proposed integrated retrofit is presented, together with the methodology used for the energy and seismic simulations. This enables to quantify the overall Expected Annual Losses (EAL), herein selected as a metric for assessing the global performance of the building. Finally,

the results are discussed and both the EAL due to the energy consumptions (EAL_E) and to the seismic damage (EAL_S) are used to assess the global performance by means of a common *Green and Resilient Indicator* (GRI), Calvi et al. (2016). The results confirm the promising advantages of using the proposed strategy for the integrated renovation of the existing building stock.

2. Research methodology and case-study application

2.1. As-Built configurations

The as built structure consists of a pre-1970's three-story RC frame building designed for gravity loads only (i.e., lacking any "capacity design principles") and in the absence of energy efficiency regulation. As a result, the building is expected to be seismically vulnerable and characterized by high annual energy consumptions.

Fig. 2 illustrates the geometric features of the building (a), together with the reinforcement details in the structural members (b). No stirrups are provided within the beam-column joints, which is typical of the construction time, and steel rebars in the beams are end-hooked anchored within the panel zone. This configuration is expected to be the most critical for existing buildings, as discussed by Pampanin et al. (2002). Furthermore, Fig.2c shows the building envelope characteristics (i.e., the vertical masonry infill walls and the roof) together with the thermal transmittance values (U-value). The windows consist of a single glazing in a timber frame, resulting in a high U-value ($4.9 \text{ W/m}^2\text{K}$) in the as-built configuration. The window-to-wall ratio is equal to 50%.

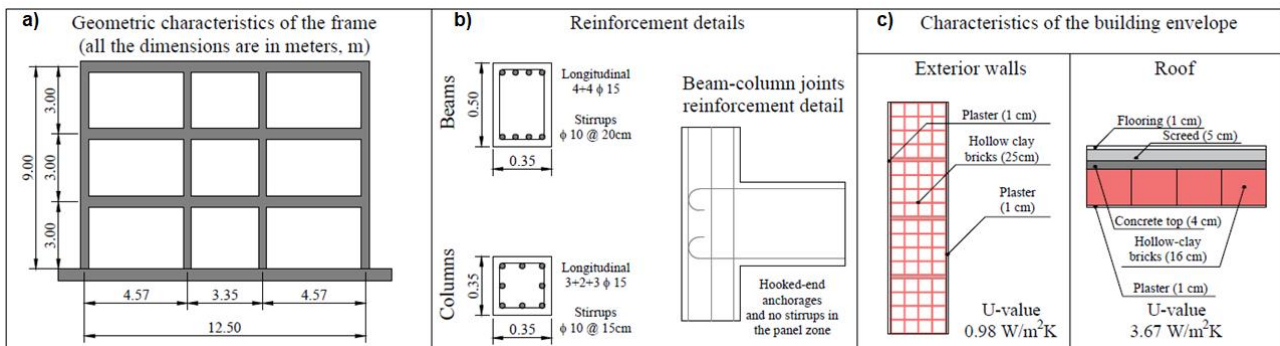


Figure 2. (a) Geometric characteristics of the frame buildings, together with (b) the reinforcement details and (c) the properties of the building envelope.

2.2. The proposed integrated retrofit approach

Fig. 3 provides a schematic representation of the proposed intervention. The seismic strengthening is provided by an external exoskeleton based on the Pres-Lam (Prestressed-Laminated Timber) technology. Specifically, Laminated Veneer Lumber (LVL) is used for the structural members. Such technology derives from the PREcast Seismic Structural System (PRESSSS) technology developed in the late 90's for RC structures, Stanton et al. (1997), Priestley et al. (1999). The main peculiarity of such a technology is the replacement of the "plastic hinges", expected in monolithic (i.e., traditional) connection systems, with a controlled "rocking & dissipative" mechanism at the end section(s) of the structural members. This low-damage system features two kinds of reinforcement, (Fig.3d): (i) a post-tensioned cable-bar designed to remain elastic, thus ensuring the self-centring capabilities of the system during the earthquake shaking; and (ii) internal mild steel, or more recently, external and replaceable fuse-type "Plug&Play" dissipaters, ensuring the energy dissipation capabilities to the system, Pampanin (2005), Sarti et al., (2016). By combining in parallel these two components, a peculiar "Flag-Shaped" hysteresis rule can be obtained, Pampanin et al. (2001). Finally, it is worth noting that an important parameter when dealing with this technology is the re-centring coefficient λ , defining how the overturning-moment is distributed among the post-tensioning/axial load and the energy dissipation devices. The connection system between the as-built structure and the external exoskeleton is ensured by prestressing bars, as suggested in Takeda et al. (2013).

Considering the high vulnerability of masonry facades, low-damage technologies are also implemented to enhance the seismic resilience of the existing envelope system thereby protecting the investment of the energy refurbishment. Specifically, the in-plane capacity of the existing masonry infill walls is enhanced by

disconnecting the monolithic panel from the surrounding frame by means of vertical and horizontal cuts to create lateral gaps. The infill wall is turned into a system consisting of individual rocking clay brick infills panels able to control the drift level after which the infills will start to experience damage. The efficiency of such a solution was proved by Tasligedik and Pampanin, (2017) through experimental 2D quasi static cyclic tests. In order to ensure the out-of-plane stability of the walls disconnected from the frame, post-installed steel plates are inserted at the top and bottom part of the system and fastened to the beams. Finally, expanded polyurethane is used for filling the gaps created by the cuts for ensuring the weather tightness of the facade and for reducing the effect of thermal bridges. Fig. 3b presents a scheme of the solution, accompanied by conceptual illustrations of the overall structural behaviour of the low-damage vs. traditional systems.

A timber-based low-damage “double-skin” facade system, infilled in the exoskeleton, has been herein proposed to improve the energy performance of the building envelope. It is worth stressing that the new cladding just introduces a small unventilated cavity, thus the second skin does not create a ventilated facade. The proposed “double-skin” system follows a similar concept introduced by Tasligedik *et al.* (2015) for low-damage timber framed drywall partitions. The facade system consists of several components. Firstly, two steel tracks are attached at the top and bottom beam. Such components provide the out-of-plane stability to the facade and allow to install friction fitted timber stud with a gap on top, which make them free to slide. As in the previous case, a vertical gap between the outermost stud and the surrounding frame should be provided to avoid the interaction with the structural system. A Cross Laminated Timber (CLT) panel and a timber fibre insulation layer are inserted within the vertical studs, and their thickness is defined to achieve a certain U-value (i.e., the thermal transmittance of the facade) according to DM 26/06, (2015), depending on the climatic zone. Specifically, the U-value to be achieved are 0.43 and 0.24 W/m²K for Messina and L'Aquila, respectively. Finally, four additional layers are included, namely: (i) an air gap, (ii) a gypsum board, to reduce the effect of the thermal bridges related to the timber studs and to the gaps in the masonry infill walls, (iii) a waterproof vapour-open membrane, and (iv) the finishing layer. The detail of the facade is shown in Fig.3e.

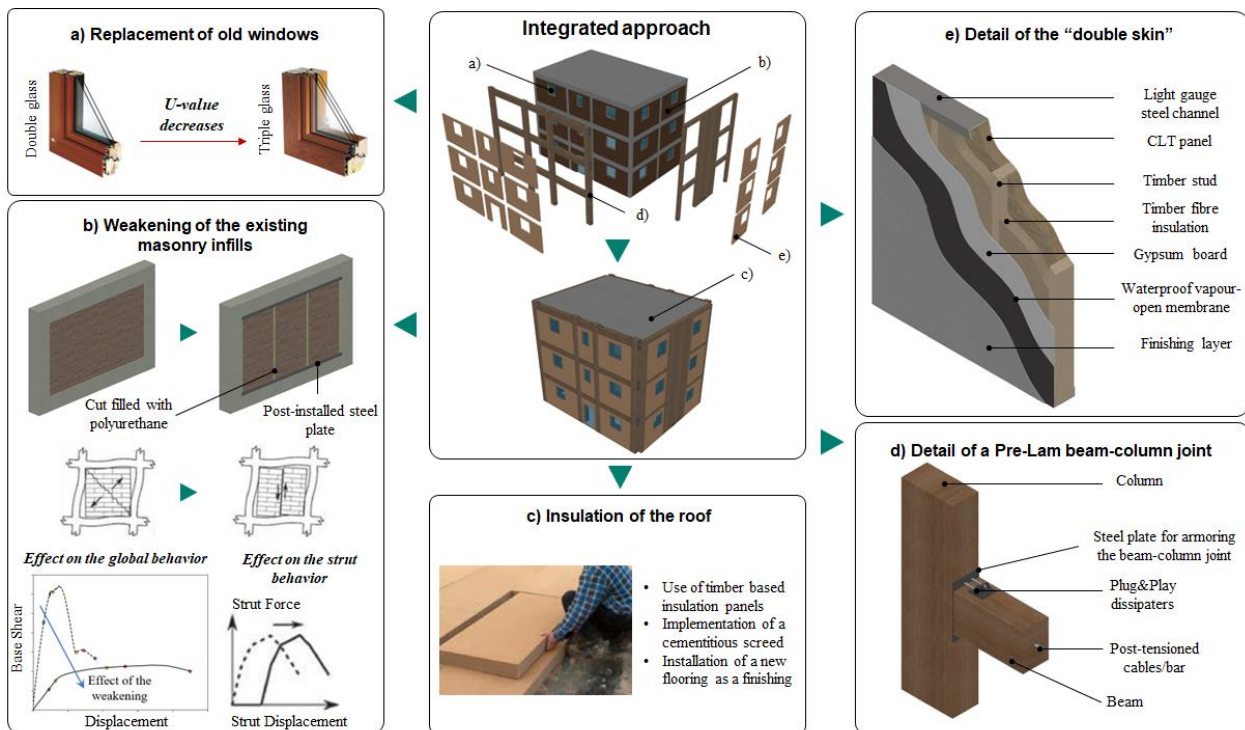


Figure 3. Schematic representation of the integrated intervention proposed, consisting of: a) replacing old windows, b) selective weakening of the existing masonry infills, c) roof insulation, d) use of Pres-Lam technology for the external exoskeleton, illustrated for a beam-column joint, and e) implementation of a low-damage timber based “double-skin” façade system for the insulation of the vertical building envelope.

Finally, in addition to the improvement of the U-values for the vertical enclosures, the insulation of the roof and the replacement of the windows, while maintaining the same window-to-wall ratio (i.e., 50%), are also considered in the refurbishment intervention. The roof is insulated by means of a timber-based panel for flat

roof. Furthermore, an additional concrete screed and a finishing layer consisting of ceramic flooring are added to protect the insulation layer itself, Fig.3d. The thickness of the layers is defined to meet the U-values imposed by DM 26/06, (2015), which are 0.35 and 0.20 W/m²K, for Messina and L'Aquila, respectively. Concerning the windows, the existing ones are replaced with a more performing double and triple glass, to meet the target U-values equal to 3.00 and 1.10 w/m²K, for Messina and L'Aquila, respectively, with low Solar Heat Gain Coefficient (SHGC = 0.55) and airtight timber frames, Fig.3a.

2.3. Seismic design of the exoskeleton through a Displacement-Based Retrofit (DBR) procedure

The external exoskeleton is designed following a Displacement-Based Retrofit (DBR) procedure. The DBR procedure is an extension of the Direct-Displacement Based Design (DDBD) procedure defined by Priestley et al. (2007) for new buildings. The DBR procedure proposed by D'Amore and Pampanin (2021) to design RC external exoskeletons is herein implemented. Such procedure aims to prevent the existing structure from reaching and exceeding the failure displacement profile. For this reason, the maximum allowable displacement for the as-built structure was considered to design the external exoskeleton. In order to be consistent with the Italian Building Code (NTC2018), this displacement was set equal to the one causing the attainment of the Life-Safety Limit State (LSLS) of the as-built structure. Such displacement was defined based on the results of non-linear static pushover (PO) analyses (further information related to the numerical modelling approach is provided in the following sections). A re-centring ratio $\lambda = 1.50$ was considered to ensure the self-centring capabilities of the retrofitted system.

Considering the behaviour of the post-tensioned timber structure when compared to the concrete system (in particular, the higher elastic deformability before the rocking motion activation), minor adjustments of the DBR procedure are considered. Specifically, in the traditional DBR procedure, the design of structural members and connections is generally carried out for the LSLS, and only subsequently the Serviceability Limit State (SLS) is checked. In case of timber components, the SLS generally govern the size of structural members and the amount of post-tensioning force, in order to provide the required stiffness to protect the non-structural components and prevent damage to the as-built structure for frequent events. Finally, a detailed connection design was carried out for LSLS to provide the correct amount of mild steel (i.e., external "Plug&Play" dissipaters) to meet the seismic demand at this limit state.

2.4. Seismic modelling and analysis

This paragraph deals with the modelling approach used for performing non-linear static push-over (PO) analyses and non-linear dynamic time history analyses (NLTHAs). Furthermore, the procedure used to define the seismic Expected Annual Losses (EALs) is also briefly described.

2.4.1 Modelling Approach

Seismic response analyses were performed through 2D numerical models implemented in the software Ruaumoko 2D, Carr (2013). Considering the as built configuration, all the information related to the lumped plasticity model herein implemented can be found in D'Amore et al. (2023). In the retrofitted cases, the exoskeleton was considered by implementing a new structural model working in parallel with the as-built structure. The two structural models are connected by means of pinned rigid links. The exoskeleton was modelled through linear elastic members (i.e., Giberson elements) with two non-linear springs working in parallel at the end sections to model both the re-centring and the dissipative behaviour related to the post-tensioned cables and to the external dissipaters, respectively. The beam-column joints were modelled through a system of rigid link and linear-springs for considering the flexibility of this components, as suggested by Di Cesare et al. (2017).

2.4.2 Seismic performance assessment

The results of the PO analyses were used to define the Safety Index (or so-called IS-V as defined according to DM 65 (2017)); and the EALs. Specifically, the IS-V is defined as the ratio between the capacity in terms of displacement and acceleration of the as built structure, to the demand, in the same terms, for an equivalent newly designed building.

The EALs were derived following the probabilistic approach based on the definition of fragility and vulnerability functions. For the seek of brevity, the main steps of the procedure are herein only outlined. Further information related to the procedure can be found in D'Amore et al. (2023). Firstly, NLTHAs were performed to define a "cloud", Jalayer et al. (2017), which correlates an Engineering Demand Parameter (EDP) with an Intensity

Measure (IM). This procedure considers both the Collapse (C) as well as Non-Collapse (NoC) cases. Specifically, the Maximum Inter-Story Drift (MIDR) was selected as an EDP, whereas the 5% damped spectrum acceleration at the fundamental period $S_a(T_1)$ was used as an IM. The EDP vs IM cloud, considering only NoC cases, was thus used to fit a power-law Probabilistic Seismic Demand Model (PSDM), $EDP = aIM^b$. On the other hand, the effect of the C cases was considered by means of a logistic regression, which is deemed appropriate to binary variables, such as C/NoC cases. By combining the PSDM with the logistic regression, it is possible to define the fragility curves for each Damage State (DS). The approach used in D'Amore et al. (2023) was adopted to identify the several DSs of both the existing and the retrofitted building. The vulnerability curves were defined considering building-level Damage-to-Loss Ratio (DLRs), available in DM 65 (2017) for each DS, to define a consequence model relating the repair-to-reconstruction costs (i.e., the Loss ratio, LR) to a given IM. Specifically, as suggested in Lagomarsino and Giovinazzi (2006), DS1 is identified when a displacement equal to $0.7d_y$ is achieved, being d_y the equivalent yielding displacement of the structure, which correspond to the attainment of DS2. DS3 and DS4 are identified by the first structural element which reach $3/4\theta_U$ and θ_U , where θ_U stands for the ultimate rotation of the member itself. Finally, DS5 is attained when a global strength reduction equal to 15% is observed. The LR for a given IM is defined as in Eq.1:

$$LR(IM) = \sum_{i=1}^5 (F_{DS_{i-1}}(IM) - F_{DS_i}(IM)) DLR_i \quad (1)$$

Where F_{DS_i} represents the fragility relationship for the generic DS. Finally, combining the vulnerability curves with the site-specific hazard analysis, the EAL_S can be defined according to Eq.2:

$$EAL_S = \int_0^{\infty} LR(IM) \left| \frac{d\lambda_{IM}}{dIM} \right| dIM \quad (2)$$

Where λ_{IM} is the Mean Annual Frequency of Exceedance (MAFE) defined from the hazard curve for the generic IM. Fig.4 illustrates a flow-chart which summarizes the procedure outlined.

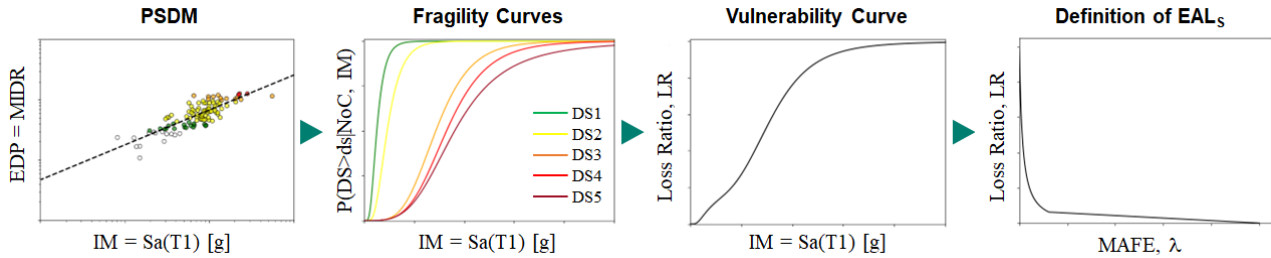


Figure 4. Flow-chart of the procedure used to define the Expected Annual Losses due to earthquakes (EAL_S)

2.5. Energy modelling and analysis

The energy performance of the case-study buildings, i.e. the as built and the refurbished configurations in both Italian locations, was assessed through dynamic simulations by implementing a model in *Grasshopper* (algorithmic modelling for *Rhinoceros*) and then running the simulation through the *EnergyPlus* software. Weather data for performing the dynamic simulations were obtained from Energy Plus Weather data (.epw) files.

First, the geometric model of the building and its thermal zones were defined in *Grasshopper*, Fig.5a. Then, the material properties (i.e., thermal conductivity, density, emissivity, specific heat) were defined for each building component and related layers (i.e., windows, roof, floors, internal partitions, and external enclosures). Following this approach, it is possible to define the thermal transmittance (i.e., the U-value) for each component. Specifically, when dealing with the external enclosures, a *Therm* model was also implemented to consider the effect of the thermal bridges in the building envelope discussed above. Fig.5b shows an example of the *Therm* model together with the results of the analysis for the case of the retrofitted vertical envelope. The U-values for each component of the envelope, together with the Solar and Heat Gain Coefficient (SHGC) of windows, are reported in Table 1. It is worth reminding that the Italian energy regulation, DM 26/06 (2015), recommends U-values for different envelope elements, as discussed in Section 2.2. Such recommendations have been used to define the characteristics of the building envelope in the retrofitted configurations.

The design requirements for the indoor comfort were set as follows. The heating set point was 20°C and the cooling one was 25°C. Referring to the data available in HoneyBee for residential buildings, the occupancy density was defined as 0.028 people/m², the electricity equipment load as 6.7 W/m², the lighting load as 6.5 W/m², the hot water production equal to 0.15 l/hm² and the infiltration rate was set equal to 0.0006 m³/m²s for the as-built configuration, while reduced to 0.0003 m³/m²s for the retrofitted structures, considering the improved weather tightness due to the replacement of the windows.

Finally, the energy simulation was performed for both sites to compute the energy consumptions. The energy costs were calculated from the electricity (0.3115 €/kWh) and gas (0.0986 €/kWh) prices provided by *Eurostat* for Italy. By using the total energy cost per year and considering a re-construction cost of the building equal to 1300 €/m², as suggested by Bianchi *et al.* (2022), the Expected Annual Losses due to the energy consumptions (EAL_E) were determined as the ratio of the energy cost for heating and cooling to the total building value, according to Calvi *et al.* (2016).

Table 1. U-values for all the envelope components for both as built and retrofitted configurations

Configuration	U-value Vertical Envelope [W/m ² K]	U-value Roof [W/m ² K]	U-value Windows [W/m ² K]	SHGC Windows
As Built	0.98	3.67	4.90	0.80
Retrofitted - L'Aquila	0.22	0.19	1.08	0.55
Retrofitted - Messina	0.25	0.30	2.80	0.55

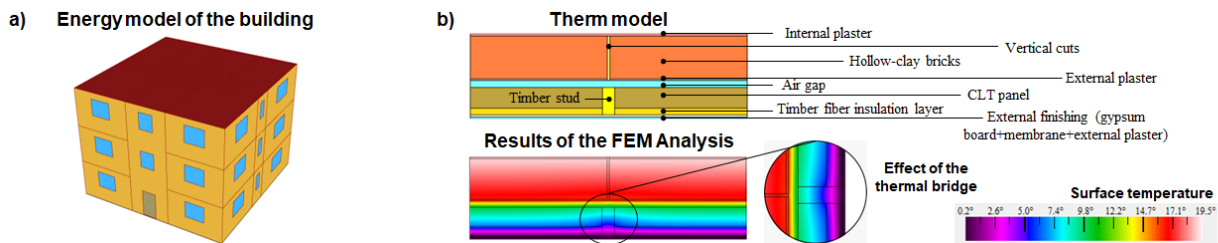


Figure 5. a) Energy model of the building developed in Grasshopper, and b) Therm model of the retrofitted vertical envelope together with the results of the thermal analysis and the effect of the thermal bridge.

3. Results and discussion

3.1. Seismic performance and loss assessment

This paragraph provides the results in terms of seismic performance and expected losses for the alternative building configurations. Firstly, a PO analysis was performed for the as-built configuration. The results of this analysis confirm that the failure mechanism of the as-built configuration is mainly governed by the brittle failure of external and internal beam-column joints. The existing structures score 56% IS-V for both locations. The same result was obtained, in terms of this index (i.e., IS-V), as the capacity is equal, being the same building located in different cities, and the demand spectra for both L'Aquila and Messina present pretty much the same spectral ordinates, as the seismic hazard is very similar. The numerical results for the existing building (particularly, the ultimate displacements at LSLs) were used as input data for designing the timber-based exoskeleton through the DBR procedure. The external exoskeleton consists of LVL structural members, where beams and columns have dimensions of 80x50 cm. Moreover, the beam-column joints were reinforced by means of steel plates connected by internal steel rods. Such reinforcement aims to limit the high elastic deformability of this component. A design drift $\theta_D = 0.95\%$ was selected to design the additional structure for both the considered locations.

Fig.6a shows the PO curves for both the as built and the retrofitted structures at LSLs. The retrofitted structures score 116% IS-V, in both locations, and even in this case the same result is obtained for the reasons explained for the as built configuration. For each configuration, the exceedance of the different DSs was defined and then used to define the fragility curves for each LS. Table 2 summarizes the maximum inter-story drift values related to the attainment of the DSs, for both the as built and retrofitted configurations, together with their

fundamental period, T_1 . Considering the retrofitted alternatives, the same external exoskeleton was designed for both locations due to almost equal seismic demand, as previously discussed.

To prove the advantages of using a low-damage (i.e., Pres-Lam) technology for the external exoskeleton, cyclic non-linear quasi-static (Push-Pull) analyses were performed to highlight the re-centring capabilities of the system. Fig.6b shows such a result together with the equivalent viscous damping ξ – defined following an area-based approach – achievable in the several cycles. Fig.6c presents the expected damage mechanisms for both the as built and retrofitted configurations at LSLs. Specifically, the comparison highlights an increase in the number of plastic mechanisms within the structure since the added stiffness, provided by the exoskeleton, forces the existing structure to deform in a more uniform and desirable manner, rather than concentrating the plastic mechanisms in limited zones.

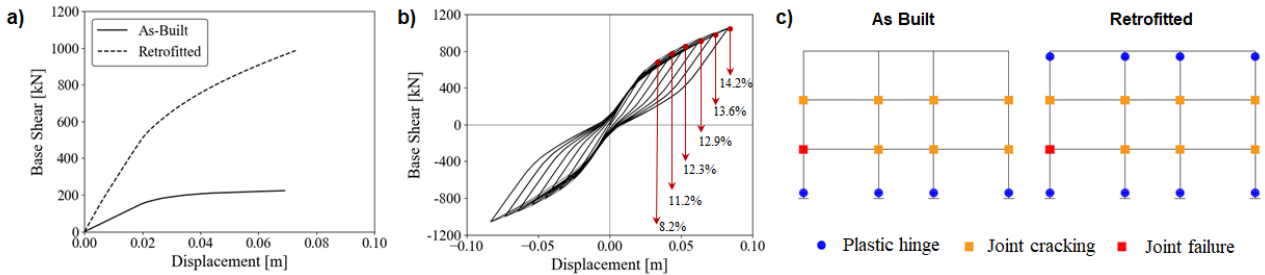


Figure 6. a) Pushover curves of the as built and retrofitted configurations, b) non-linear static cyclic push-pull analyses of the retrofitted configuration, and c) observed damage mechanisms at LSLs.

Table 2. Maximum inter-story drift values at the different DSs, together with the fundamental period, for the as built and retrofitted buildings.

Configuration	Drift DS1	Drift DS2	Drift DS3	Drift DS4	Drift DS5	T_1 [sec]
As Built	0.23%	0.33%	0.95%	1.21%	2.97%	0.808
Retrofitted	0.31%	0.43%	0.98%	1.22%	2.71%	0.419

NLTHAs were performed using 150 earthquake records defined according to the procedure described in section 2.4.2. The results from such analyses were used to define a PSDM for both the as built and retrofitted configurations. The parameters a and b of the PSDM are summarized in Table 3. These parameters are used for both locations, where the same structural models and records were considered when performing NLTHAs, as explained before.

Table 3. Parameters of the PSDM (a , b), together with the median (μ) and standard deviation (β) values of the fragility curves for all the DSs.

Configuration	a	b	DS1 (μ , β)	DS2 (μ , β)	DS3 (μ , β)	DS4 (μ , β)	DS5 (μ , β)
As Built	2.229	0.817	0.061, 0.314	0.097, 0.314	0.351, 0.307	0.461, 0.293	0.758, 0.310
Retrofitted	0.692	0.668	0.294, 0.308	0.494, 0.307	1.435, 0.287	1.669, 0.316	1.807, 0.395

Fragility estimation is then performed by using the fitted power-law PSDM together with the results from the logistic regression, which considers the collapsed and non-collapsed cases. The median values, μ , and the logarithmic standard deviation, β , for the fragility curves are also summarized in Table 3. Using the results from the fragility analysis, together with the DLRs defined according to DM 65 (2017), the vulnerability curves can be defined. Finally, by combining the results from the vulnerability curves with the site-specific hazard curves, the EALs was computed. For defining an analytical formulation of the hazard curve, a wide interval was considered for the second-order biased fit proposed by Vamvatsikos (2014). Such approach requires the definition of three coefficients, namely k_0 , k_1 and k_2 . The values of k_0 are 0.001074 and 0.001207, for k_1 are 3.5336 and 2.5402, and for k_2 are 0.6406 and 0.2451, for L'Aquila and Messina, respectively. The derived values of EALs are 1.63% and 1.28% for the as built configurations, and 0.53% and 0.48% for the retrofitted ones, for L'Aquila and Messina respectively. In both cases, a drastic reduction of the EALs can be noted,

pointing out the efficiency of such a technology for retrofitting existing buildings from a seismic safety point of view. Furthermore, it is highlighted that the results of EALs for the retrofitted configuration are expected to be quite conservative, as the DLR model used (“White Book” (2016), DM 65 (2017)) does not consider the advantages of using the Pres-Lam low-damage technology (e.g., reduced time and costs for repair activities).

3.2. Energy performance and loss assessment

The dynamic energy simulation results provide the monthly energy consumptions for each building configuration in the two considered locations. As an example, Fig.7 shows this outcome for the as-built configuration for L’Aquila (a) vs. Messina (b).

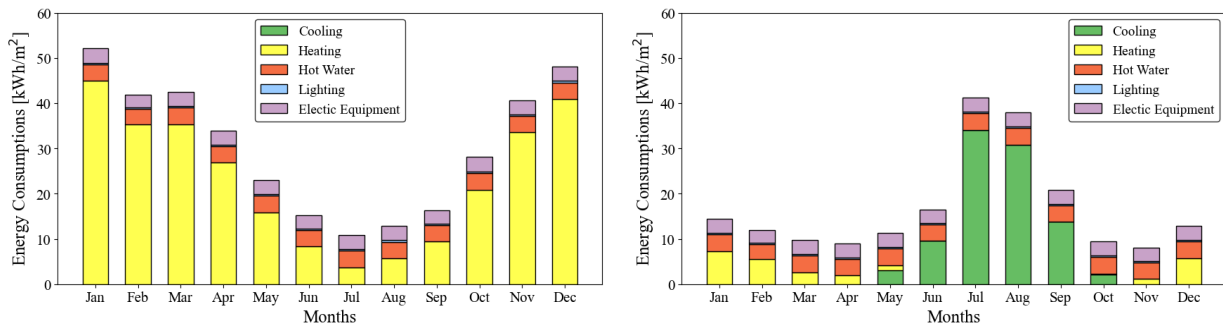


Figure 7. Monthly energy consumptions for the as-built configuration for L’Aquila (a) and Messina (b).

The figure highlights the significant differences between the two climatic conditions especially in terms of energy consumptions related to heating and cooling. Meanwhile, energy consumptions related to hot water production, lighting, and electric equipment are constant throughout the year. It is worth noting that there is no cooling demand for L’Aquila, in fact there is a heating demand in the as-built configuration, even in summer. This is related to the cold climate registered on top of Monte Terminillo (more than 2000 m above sea level), from which weather data are obtained for L’Aquila. Additionally, such result is influenced by the poor characteristics of the building envelope in the as-built configuration.

Table 4. Main results obtained from the energy simulations for both the configurations and locations considered. (AB: As Built, R: Retrofitted)

Configuration	Energy Cons. [kWh/m ²]	Energy Cons. Savings [%]	Energy Cost [€]	Energy Cost Savings [%]	EAL _E [%]
AB L’Aquila	365.82	---	17.7k	---	2.14%
AB Messina	203.94	---	19.4k	---	2.44%
R L’Aquila	126.81	65%	8.5k	52%	0.32%
R Messina	133.69	35%	12.7k	35%	1.14%

Table 4 summarizes the main results obtained from the energy simulations. The total energy consumption values for the as-built configurations are 365.82 kWh/m² and 203.94 kWh/m², with energy costs of 17.7 k€ and 19.4 k€ for L’Aquila and Messina, respectively. Despite L’Aquila showing notably higher energy consumptions compared to Messina, the latter city exhibits a higher energy cost. This difference can be attributed primarily to the high electrical energy demand (pertaining to cooling costs), which exceed the cost of gas (associated with heating expenses) by over threefold. Considering the refurbished configurations, a drastic decrease in both the energy consumptions and related costs can be noticed. Specifically, the energy consumptions are equal to 126.81 kWh/m² and 133.69 kWh/m², with energy costs of 8.5 k€ and 12.7 k€, for L’Aquila and Messina, respectively. In this case, the energy consumptions are almost the same, and the difference in the costs is justified by the same considerations made above. Considering such results, it is possible to highlight a reduction in the energy consumptions equal to 65% and 35%, whereas considering the economic savings, the reduction values are 52% and 35%, for L’Aquila and Messina respectively. Finally, it is possible to define the EAL_E values, equal to 2.14% and 2.44% to 0.32% and 1.14%, for L’Aquila and Messina, after the retrofit intervention. Once again, considering the higher cost of electricity it is found that the EAL_E remain quite high

for the buildings located in the hot climate even in case of energy refurbishment. For this reason, in the future developments of this work, also alternative cooling strategies (e.g., night cooling passive strategy, implementation of ventilated facade systems) or use of solar blinds will be assessed.

3.3. Integrated seismic and energy performance classification

This section assesses the benefits of an integrated renovation strategy based on the double-skin exoskeleton proposed in this work. Specifically, the combined seismic and energy performance is evaluated through a single value, namely a Green and Resilient Indicator (GRI), Calvi et al. (2016), which is a function of both EAL_E and EAL_S . Specifically, considering the energy classes defined in the mentioned work, together with the ones proposed in the DM 65 (2017) for the seismic performance, the combined class can be defined as in Fig.8a. The classification from A+ to F is adopted, where A+ indicates the best performance while F the worst. The figure presents the results for the as built and for the retrofitted configurations for both locations. The as built configuration is ranked with a C class for both L'Aquila and Messina. After the retrofit interventions, the building located in L'Aquila increases its performance from C to A, whereas it moves from C to B for Messina.

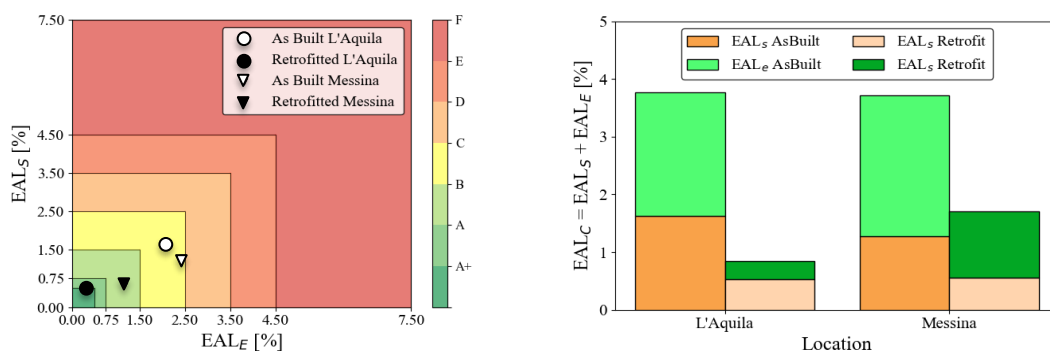


Figure 8. (a) GRI classification, and (b) combined EAL_C for both locations and configurations.

Furthermore, Fig.8b shows the results in terms of combined expected annual losses (EAL_C) defined as the sum of both economic losses, EAL_E and EAL_S , defined in the previous section. The values of EAL_C decrease from 3.77%/3.72% to 0.85%/1.62% for L'Aquila/Messina with a total economic saving of 75%/56%. The figure shows that the higher value of losses for Messina is due to the EAL_E , as the EAL_S are approximately the same for both locations after the retrofit intervention. As discussed above, this is mainly related to the major energy consumptions for cooling in a hot climate. The cooling load is associated with the electricity, which is more expensive than gas (used for heating) that is predominant in cold climate (e.g., L'Aquila). Table 5 summarizes the loss values (EAL_S , EAL_E and EAL_C) for both locations for the case-study buildings.

Table 5. Value of the Expected Annual Losses for both configurations and locations.

EAL	L'Aquila AsBuilt	L'Aquila Retrofit	Messina AsBuilt	Messina Retrofit
EAL_S	1.63 %	0.53%	1.28%	0.48%
EAL_E	2.14%	0.32%	2.44%	1.14%
$EAL_C = EAL_S + E$	3.77%	0.85%	3.72%	1.62%

4. Conclusions

This paper has proposed and investigated an integrated approach for the holistic renovation of the existing RC building stock. Specifically, such strategy exploits an external low-damage timber-based exoskeleton (i.e., implementing the Pres-Lam technology) equipped with low-damage high performing "double-skin" facade systems. The exoskeleton ensures the seismic strengthening to the building, while the "double skin" allows for both an energy and architectural upgrade of the existing building.

The effectiveness of the proposed strategy was assessed for an existing RC case-study building located in two different Italian cities, characterized by a similar high-seismicity level but different climatic conditions (a cold climate, L'Aquila, and a warm climate, Messina). Non-linear (dynamic) time-history analyses were performed for the as-built and retrofitted configurations to define the expected annual losses (EAL_S) following

a probabilistic-based approach (i.e., based on the definition of fragility and vulnerability functions). Furthermore, dynamic energy analyses were conducted for defining the energy consumption of the buildings, and the associated economic losses (EAL_E).

The outcomes from seismic and energy analyses were finally combined to define the building performance by means of a comprehensive and common Green and Resilient Indicator (GRI). The numerical results show a drastic decrease of the losses related to both seismic damage and energy consumptions, confirming the high potential and attractiveness of the proposed integrated intervention. More specifically, the total loss EAL_C (defined as the sum of EAL_S and EAL_E) decreases from 3.77% and 3.72 % to 0.85% and 1.70%, for L'Aquila and Messina respectively, with a total economic saving on the combined losses equal to 75% and 54%. Furthermore, the combined GRI performance class, is improved from C to A and from C to B for L'Aquila and Messina, respectively. The energy saving for Messina, and the corresponding shift in the GRI class, is not as significant as that of L'Aquila due to the higher cooling demand expected in the warm climate of Messina. Such a demand requires electricity which is three times higher than the gas required for the heating demand in L'Aquila, Nevertheless the results are very promising. Further improvements are possible by for example: (i) developing a more refined component-based loss assessment procedure that can be implemented for assessing the advantages related to the use of low-damage technologies, rather than traditional ones, thereby evaluating EAL_S more accurately; (ii) further reducing the energy losses (EAL_E) in warm climates by implementing energy saving strategies such as nighttime cooling, ventilated facade systems and the use of solar shading.

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6. References

- Artola, I., Rademaekers, K., Williams, R. and Yearwood, J. (2016). *Boosting building renovation: What potential and value for Europe?*, European Union, Brussels.
- Belleri, A. and Marini, A. (2016). Does seismic risk affect the environmental impact of existing buildings? *Energy and Buildings*, 110:149–158.
- Bianchi, S., Ciurlanti, J., Overend, M. and Pampanin, S. (2022). A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings. *Engineering Structures* 269, p.114852.
- Calvi, G.M., Sousa, L. and Ruggeri, C. (2016). Energy efficiency and seismic resilience: A common approach. *Multi-Hazard Approaches to Civil Infrastructure Engineering*. Springer International Publishing, 165–208.
- Carr, A.J. (2013). *Ruaumoko 2D-computer program for inelastic time history analysis of structures*. Christchurch, New Zealand: University of Canterbury.
- D'Amore, S. and Pampanin, S. (2021). Seismic Retrofit of Reinforced Concrete buildings using low-damage external exoskeletons. *Proceedings of the 2nd fib YMG Symposium on Concrete and Concrete Structures*. Rome, Italy.
- D'Amore, S., Pedone, L. and Pampanin, S. (2023). Alternative retrofit strategies for seismic risk reduction: Studying the effectiveness of low-damage external exoskeletons. *Proceedings of the 9th COMPDYN Conference*. Athens, Greece.
- Di Cesare, A., Ponzio, F.C., Nigro, D., Pampanin, S. and Smith, T. (2017). Shaking table testing of post-tensioned timber frame building with passive energy dissipation systems. *Bulletin of Earthquake Engineering*, 15(10):4475–4498.
- Dolce, M. and Manfredi, G. (2016). *Libro Bianco Sulla Ricostruzione Privata Fuori dai Centri Storici nei Comuni Colpiti dal Sisma dell'Abruzzo del 6 Aprile 2009*. (In Italian). Napoli: Doppiavoce.
- Jalayer, F., Ebrahimian, H., Miano, A., Manfredi, G. and Sezen, H. (2017). Analytical fragility assessment using unscaled ground motion records. *Earthquake Engineering and Structural Dynamics*, 46:2639-2663.

- Lagomarsino, S., and Giovinazzi, S. (2006). Macro seismic and mechanical models for the vulnerability and damage assessment of current buildings. *Bulletin of Earthquake Engineering*, 4:415-443.
- Manfredi, V. and Masi, A. (2018). Seismic strengthening and energy efficiency: Towards an integrated approach for the rehabilitation of existing RC buildings. *Buildings*, 8(3):36.
- Margani, G., Evola, G., Tardo, C. and Marino, E.M. (2020). Energy, seismic, and architectural renovation of RC framed buildings with prefabricated timber panels. *Sustainability*, 12(12):4845.
- Marini, A., Passoni, C., Belleri, A., Feroldi, F., Preti, M., Metelli, G., Riva, P., Giuriani, E. and Plizzari, G. (2017). Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept. *European Journal of Environmental and Civil Engineering*, 8189:1–21.
- Ministerial Decree. (2015). *DM 25/06 Application of the methodologies for the calculation of the building energy performance and for the definition of provisions and minimum requirements for buildings*. Rome, Italy.
- Ministerial Decree. (2017). *DM 65/2017 Linee Guida per la Classificazione del Rischio Sismico delle Costruzioni (in Italian)*, Rome, Italy.
- Ministero delle infrastrutture e dei trasporti. (2018). *Aggiornamento delle Norme tecniche per le costruzioni. Gazzetta Ufficiale Serie Generale 42 (in Italian)*. Rome, Italy.
- Palermo, A., Pampanin, S. and Buchanan, A.H. (2006). Experimental investigations on LVL seismic resistant wall and frame subassemblies. *Proceedings of the 1st European Conference on Earthquake Engineering and Seismology (ECEES)*. Geneva, Switzerland.
- Palermo, A., Pampanin, S., Buchanan, A. and Newcombe, M. (2005). Seismic design of multi-storey buildings using laminated veneer lumber (LVL). *Proceedings of the NZ Society of Earthquake Engineering Annual Conference*. Taupo, New Zealand.
- Pampanin, S., Priestley, M. J. N., and Sritharan, S. (2001). Analytical modelling of the seismic behaviour of precast concrete frames designed with ductile connections. *Journal of Earthquake Engineering*, 5(03):329–367.
- Pampanin, S. (2005). Emerging solutions for high seismic performance of precast/prestressed concrete buildings. *Journal of Advanced Concrete Technology*, 3(2):207–223.
- Pampanin, S., Calvi, G.M. and Moratti, M. (2002). Seismic behaviour of RC beam-column joints designed for gravity loads. *Proceedings of the 12th European Conference on Earthquake Engineering*. London, UK.
- Priestley, M.J.N., Calvi, G.M. and Kowalsky, M.J. (2007). *Direct Displacement-Based Seismic Design of Structures*, 2nd Ed., Pavia: Fondazione EUCENTRE
- Priestley, M.J.N., Sritharan, S., Conley, J.R. and Pampanin, S. (1999). Preliminary results and conclusions from the PRESS five-story precast concrete test building. *PCI journal*, 44(6):42–67.
- Sajn, N. (2016). *Energy efficiency of buildings: A nearly zero-energy future. European Parliamentary Research Service*, European Union, Brussels.
- Sarti, F., Palermo, A. and Pampanin, S. (2016). Fuse-Type External Replaceable Dissipaters: Experimental Program and Numerical Modeling. *Journal of Structural Engineering*, 142(12).
- Stanton, J., Stone, W.C., and Cheek, G.S. (1997). A hybrid reinforced precast frame for seismic regions. *PCI journal*, 42(2):20–32.
- Takeda, K., Tanaka, K., Someya, T., Sakuda, A. and Ohno, Y. (2013). Seismic retrofit of reinforced concrete buildings in Japan using external precast, prestressed concrete frames. *PCI Journal*, 58(3):41–61.
- Tasligedik, A.S. and Pampanin, S. (2017). Rocking Cantilever Clay Brick Infill Wall Panels: A Novel Low Damage Infill Wall System. *Journal of Earthquake Engineering*, 21(7):1023–1049.
- Tasligedik, A.S., Pampanin, S. and Palermo, A. (2015). Low damage seismic solutions for non-structural drywall partitions. *Bulletin of Earthquake Engineering*, 13(4):1029–1050.
- Vamvatsikos, D. (2014). Accurate Application and Second-Order Improvement of SAC/FEMA Probabilistic Formats for Seismic Performance Assessment. *Journal of Structural Engineering*, 140(2).
- Zanni, J., Cademartori, S., Marini, A., Belleri, A., Passoni, C., Giuriani, E., Riva, P., Angi, B., Brumana, G. and Marchetti, A.L. (2021). Integrated Deep Renovation of Existing Buildings with Prefabricated Shell Exoskeleton. *Sustainability*, 13(20).