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Enhancing seismic and climate resilience of existing buildings through low-damage external exoskeletons

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Abstract. In recent years, devastating earthquakes and climate-induced events have raised societal awareness of the urgent need to enhance resilience against extreme hazards. This becomes crucial when dealing with existing buildings. Many of these structures were built before the enforcement of modern seismic codes and energy regulations. Consequently, existing buildings are exhibiting a lack of resilience not only during earthquakes but also in case of extreme climatic conditions. Moreover, the energy inefficiency of the building stock should not be viewed solely as a problem related to its thermal vulnerability. It also requires an unprecedented effort to meet the goals outlined in the European Green Deal, specifically targeting energy savings and decarbonization by 2030 and 2050, respectively, to increase environmental sustainability.

This work explores the feasibility of employing external low-damage exoskeletons consisting of rocking-dissipative structural connections for seismic strengthening. The implementation of exoskeletons is nowadays crucial, given the possibility of carrying out the intervention from the outside with limited disruption for occupants. Moreover, the exoskeleton serves as a support for a “double-skin” facade system offering opportunities to enhance the envelope energy performance, thereby enabling an integrated (i.e., seismic and energetic) rehabilitation.

This paper discusses the advantages of using external exoskeletons compared to more traditional strategies (e.g., seismic local interventions combined with thermal coatings) by a case study application. The overall performance of as-built and retrofitted configurations is assessed through seismic and energy dynamic analyses as well as integrated loss modeling for resilience evaluations. The findings provide evidence of the efficiency of the proposed strategy and its potential.

Keywords: Integrated rehabilitation, Existing buildings, External exoskeletons, Low-damage technologies, Sustainable renovation, Energy efficiency.

1 Introduction

In recent years, devastating earthquakes have confirmed once again the extreme structural/seismic vulnerability of existing Reinforced Concrete (RC) buildings, particularly those constructed before the enforcement of seismic codes. Additionally, existing buildings are characterised by high energy consumption related to the poor performance of their envelope, defined in the absence of proper energy regulations. Therefore, it is nowadays clear the urgent need to opt for integrated renovation strategies aiming at reducing seismic vulnerability, while also improving energy performances. This enables to enhance both seismic resilience and environmental sustainability of the built environment, by reducing energy consumption/costs and associated Green House Gas (GHG) emissions. In addition to energy

consumption, the operations related to repair activities or the need to demolish and rebuild damaged buildings should be considered as they have substantial impact on the GHG emissions. This further confirms the need to select integrated high-performance interventions. Indeed, the renovation of the existing building stock, in combination with the construction of resilient and nearly-zero energy buildings, could play an important role in achieving a reduction of energy consumption and GHG emissions equal to 80% and 90%, respectively, by 2050 [1].

To this end several strategies and techniques are nowadays available for improving the seismic performance of buildings. These can be grouped into two main categories, namely: i) local, and ii) global ones. Local strategies (i.e., use of Fibre-Reinforced Polymers FRP, implementation of Concrete Jacketing CJ, etc.) aim at modifying the hierarchy of strength within beam-column joint subassemblies, thus preventing brittle failure mechanisms (e.g., shear failure of the panel zone), and enabling more ductile ones (e.g., beam hinging). Nevertheless, local strategies generally require local demolitions for their implementation, and consequently, a high level of invasiveness/disruption, which generally requires the relocation of building occupants. Consequently, building owners typically opt for the light-only-energy intervention, which could be easily impaired in case of frequent earthquakes, and loss - potentially together with the whole building - in case of a rare (i.e., strong) event, further pointing out the importance of combined or integrated renovation strategies [2]. Building on these considerations, it is easy to understand the growing interest of the scientific community in global interventions (i.e., aiming at modifying the whole structural response) based on external exoskeletons. Indeed, the exoskeleton can be implemented from outside the building with negligible/limited disruption for the occupants. Moreover, the exoskeleton, which ensures the seismic retrofit, can be used as the support for a high-performance “double-skin” facade system, allowing a holistic renovation with energy upgrade and architectural restyling, Fig. 1. For this reason, in the last years, several exoskeleton solutions have been proposed in the literature, also adopting different materials. For instance, Marini *et al.* [3] proposed a steel exoskeleton, equipped with alternative double-skin solutions depending on the orientation of the facade. Manfredi & Masi [4] assessed the advantages of using external infilled RC exoskeletons, while Margani *et al.* [5] proved the efficiency of exoskeleton solutions based on Cross-Laminated Timber (CLT) panels for the holistic renovation.

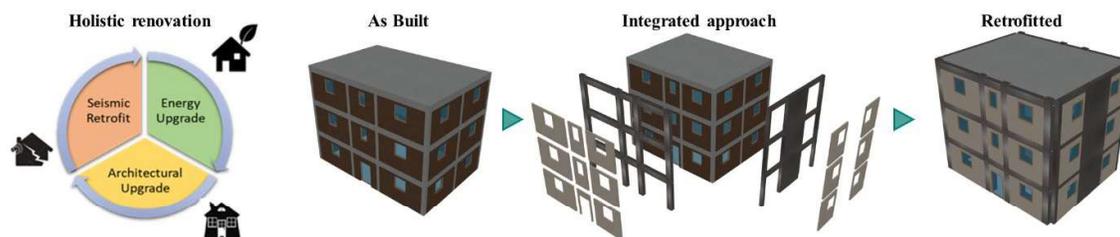


Fig. 1. Schematic representation of the holistic renovation based on external exoskeletons (modified after D’Amore *et al.* [6]).

Considering the aforementioned advantages of using external exoskeleton solutions, this paper discusses the effectiveness and attractiveness of adopting external integrated low-damage exoskeletons based on the PREcast Seismic Structural System (PRESSS) technology [7–9]. The efficiency of the proposed solution is herein assessed through a case-study application on an existing RC building located in different Italian cities (i.e., L’Aquila and Reggio Calabria), considering alternative renovation strategies to compare it with typical interventions widely used in practice. After describing the case-study and all the renovation alternatives, Section 2 presents the methodology adopted to perform both seismic and energy simulations. Finally, building on the results of the simulations, the global performances are assessed in terms of Expected Annual Losses (EAL) (Section 3). More specifically, both the EAL related to seismic hazard (i.e., EAL_S) and the ones related to energy consumption (EAL_E) are defined and combined for assessing two decision-support indicators, namely: i) the combined/cumulative losses (EAL_C) and ii) the Green and Resilient Indicator (GRI) introduced by Calvi *et al.* in 2016 [10].

2 Methodology and case study application

2.1 As-built configuration

The as-built structure consists of a 5-storey pre-1970 RC frame building with a squared floor-plan, and designed in the absence of modern seismic codes and energy regulations. The case-study building has been located in two cities in Italy, namely, L'Aquila and Reggio Calabria. The two cities have a similar high seismic hazard, whereas the climatic conditions are different. According to DM 26/06 2015 [11], L'Aquila is located in a cold climate, while Reggio Calabria in a warm one. Fig. 2a presents the geometric characteristics of the building, while Fig. 2b illustrates the reinforcement details. Finally, Fig. 2c shows the geometric characteristics of the building envelope (i.e., external walls and roof), together with the values of the thermal transmittance (i.e., the U-value). The window-to-wall ratio is equal to 15%, and the windows consist of a single glazing in a timber frame, resulting in a U-value equal to $4.9\text{W/m}^2\text{K}$.

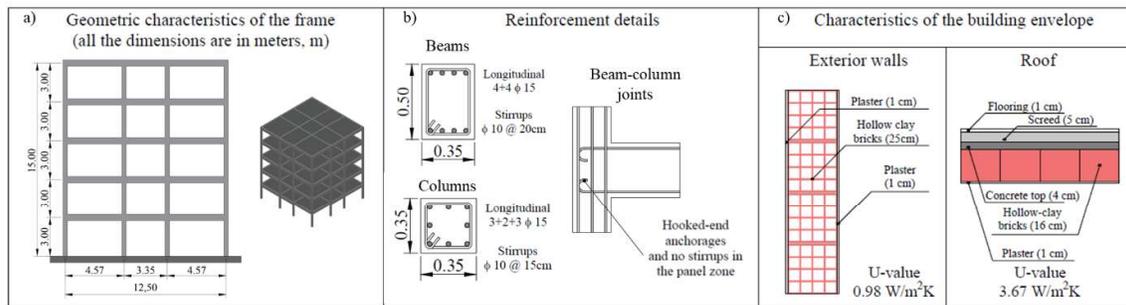


Fig. 2. a) Geometric characteristics of the RC frame building, b) reinforcement details, and c) geometric characteristics and properties of the building envelope.

2.2 Traditional combined approaches vs. proposed integrated solution based on external low-damage exoskeletons

In this work, alternative renovation strategies were to prove the advantages of implementing the solution based on external low-damage exoskeletons. The first two alternatives were based on the implementation of seismic local interventions combined with a thermal coat. The third one was based on a low-damage exoskeleton equipped with a high-performing double-skin solution. Solution 1 is based on the use of Carbon FRP (CFRP) for external and internal beam-column joints strengthening, as well as for enhancing the ductility of columns. On the other hand, Solution 2 is based on the implementation of a CJ. Both solutions (i.e., Solution 1 and 2) were combined with the implementation of a thermal coat based on expanded polyurethane (EPS) panels. The thickness of the EPS panels was selected in order to meet the U-values required by DM 26/06 [11] for the vertical envelope in the two considered cities (i.e., 0.43 and $0.24\text{w/m}^2\text{K}$ for Reggio Calabria and L'Aquila, respectively). Fig. 3a presents a schematic representation of the two solutions.

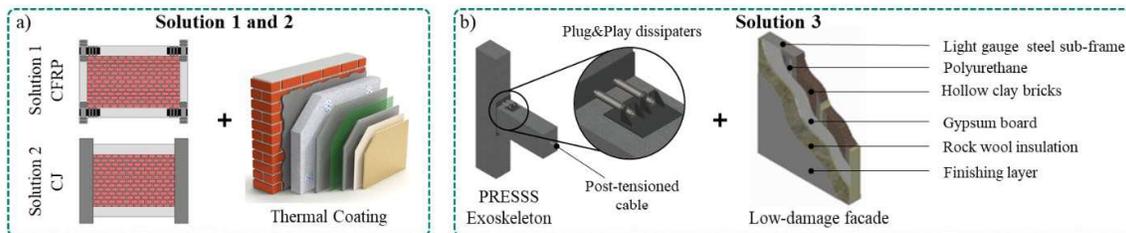


Fig. 3. a) Schematic representation of the combined solutions based on local seismic strengthening techniques and thermal coat, and b) solution based on the external low-damage exoskeleton equipped with high-performing double skin systems.

As previously mentioned, Solution 3 (Fig. 3b) is based on the implementation of a low-damage exoskeleton based on the PRESS technology. The main peculiarity of this technology is the replacement of the plastic hinge formation with a peculiar and controlled “rocking & dissipative” mechanism at the interface between structural members. The connections of the system are based on two types of reinforcement. The first one is a post-tensioned cable/bar designed to remain elastic, and thus able to ensure the closure of the pre-existing gaps between components after the earthquake shaking. The second is featured by internal rebars, or more recently and preferably, external and replaceable *Plug & Play* dissipaters which ensure the energy dissipation capabilities of the system [8,12]. By combining in parallel these two types of reinforcement, a peculiar “flag-shape” hysteresis rule is obtained [13]. Additionally, it is worth mentioning that one of the most important parameters to account for when dealing with such a technology is the re-centering ratio λ . Such a coefficient defines how the overturning moment is distributed among the *Plug & Play* dissipator and the post-tension [14]. The connection between the as-built structure and the exoskeleton is ensured by prestressing bars or additional slabs depending on whether the exoskeleton is adherent or distanced from the as-built structure [15]. Moreover, considering the high seismic vulnerability of the existing masonry infills, low-damage technologies are also implemented for the building envelope. More specifically, the existing infills are disconnected from the surrounding frame by operating vertical and horizontal cuts. The gaps introduced by these cuts enable the behavior of the infill to be turned from that of a single squat panel to a series of rocking cantilever panels. This change of behavior delays the development of the strut action, which can develop only when the gap closure occurs, thus enhancing the seismic resilience of the facade. This selective weakening approach allows reproducing the behavior of the high-performing masonry infill system proposed and tested by Tasligedik & Pampanin in 2017 [16]. Further information related to such a selective weakening, also addressing out-of-plan considerations, can be found in D’Amore *et al.* [6]. Finally, the double-skin system is based on the solution proposed by the same authors [16] and thus on independent rocking cantilever clay-brick infill wall panels built within a light-gauge steel subframe. The thickness of the clay bricks is equal to 150mm. Furthermore, a 10mm gypsum board panel is installed on the external side of the facade to reduce the effect of the thermal bridge introduced by the steel subframe. The thickness of the rock wool insulation layer is defined to meet the U-values required by the national code [11] for the two different cities. Finally, a 10mm finishing layer is considered. A schematic representation of the double skin is provided in the right part of Fig. 3b. For all the retrofit alternatives (i.e., Solution 1, 2, and 3), EPS panels were applied for the insulation of the roof. Moreover, the old windows were replaced with new double-pane ones. As for the vertical envelope, the thickness of the EPS panels and the characteristics of the windows were defined to meet the requirements of DM 26/06 [11] for both locations. Finally, solar blindings consisting of louvres were also considered for the warm climate of Reggio Calabria.

2.3 Seismic analysis

Modelling approach. Seismic analyses were performed by implementing lumped plasticity numerical models in Ruaumoko [17]. Detailed information related to the modeling approach both the as-built configuration as well as all the retrofit alternatives can be found in D’Amore *et al.* [18]. Such a modelling approach enables to perform both non-linear static (pushover) analyses and non-linear time history analyses (NLTHAs).

Seismic performance assessment. To evaluate the seismic performance of the alternative configurations, the Safety Index (i.e., IS-V defined as Capacity/Demand ratio, by the “*Italian Guidelines for Seismic Risk Classification of Constructions*” [19] corresponding to the %New Building Standard, &NBS defined in the NZSEE2017 Seismic Assessment Guidelines [20]) was derived by using the results of pushover analyses. Such an index can be defined as the ratio between the capacity of the considered structure, in terms of displacements/accelerations, to the demand, in the same terms, on an equivalent newly designed building. Moreover, the economic index related to the EALs was defined using a probabilistic approach based on fragility and vulnerability curves. The full procedure herein adopted can be found in D’Amore *et al.* [18]. Here, only the main steps of the procedure are briefly discussed. Firstly, NLTHAs were performed on the different configurations (i.e., as-built and retrofitted structures). A

“cloud analysis” was employed to relate the Engineering Demand Parameter (*EDP*) to an Intensity Measure (*IM*) [21]. In this study, the cloud analysis considers both Collapse (*C*) and Non-Collapse Cases (*NoC*) [21]. The *EDP* considered in this study is the Maximum Inter-Story Drift (*MIDR*), while the 5%-damped spectrum acceleration at the fundamental period ($S_a(T_1)$) was adopted as an *IM*. The cloud relating the *EDP* vs. *IM* was used to fit a Probabilistic Seismic Demand Model (*PSDM*), while the effect of *C* cases was considered by means of a logistic regression. By combining the information related to both the *PSDM* and the logistic regression, fragility curves for all the five considered Damage States (*DSs*) were defined. According to Lagomarsino & Giovinazzi [22], *DS1* is identified by achieving a displacement equal to $0.7d_y$, where d_y stands for the equivalent yielding displacement of the structure. d_y also defines the attainment of *DS2*. The remaining *DSs*, are defined according to the *Italian Building Code* [23]. More specifically, *DS3* and *DS4* are reached when the first member achieves a rotation equal to $3/4\theta_u$ and θ_u , respectively, being θ_u the ultimate rotation. Finally, *DS5* is achieved when a global strength reduction equal to 15% is observed. Vulnerability functions were thus built by using building-level Damage-to-Loss Ratios (*DLRs*) available in the national guidelines [19] for each *DS*. This allowed to define a consequence model relating the repair-to-reconstruction costs to a specific *IM*. Finally, the EAL_S can be defined by combining the vulnerability functions with the site-specific hazard analysis, as summarized in Fig. 4.

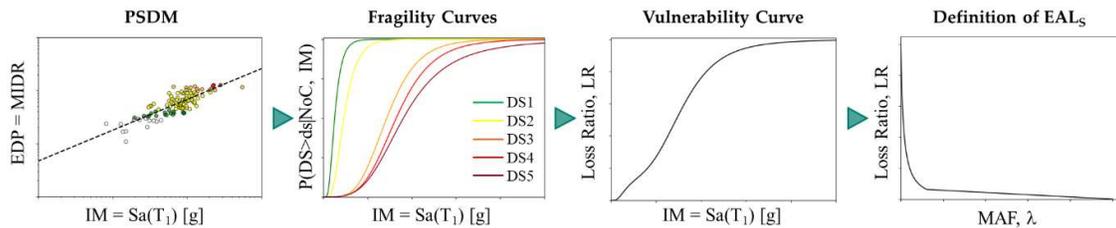


Fig. 4. Flow-chart of the procedure used for defining the economic losses (i.e., EAL_S). D’Amore *et al.*, [6].

2.4 Energy analysis

The energy performance of all the building alternatives in both cities was defined by implementing energy models in Grasshopper and then running numerical simulations with the EnergyPlus software [24]. Weather data for performing the aforementioned simulations were described in terms of Energy Plus Weather (.epw) files. The numerical models were implemented by defining the geometry of the case-study buildings. Then, material properties were assigned to each component and related layers of building components. This allows the model to define the U-value for each component, which is essential to perform the energy simulations. The design requirements for indoor comfort, adopted for performing the simulations, are available in D’Amore *et al.* [6]. Finally, building on the results of the energy simulations, the energy consumption, together with the related energy losses, were defined. The energy costs were computed according to the electricity and gas costs provided by Eurostat for Italy. Such costs are equal to 0.3782 €/kWh and 0.0981 €/kWh, for electricity and gas, respectively. Moreover, considering a re-construction cost equal to 1300 €/m² [25], the EAL_E was derived as the ratio between the energy cost related to heating and cooling, to the total building value [10].

3 Results and discussion

3.1 Seismic design of the retrofit alternatives

As mentioned above, several technical solutions were considered in this study, namely the use of Carbon Fiber Reinforced Polymers (CFRP), the implementation of the Concrete Jacketing, CJ, and the installation of an external low-damage exoskeleton. Concerning the interventions based on CFRP, both internal and external beam-column joints at the first 4 stories were strengthened. Moreover, a full wrapping of all the columns in the first 2 stories was considered for improving the ductility of such structural

members. The same intervention was considered for both L'Aquila and Reggio Calabria. When dealing with the CJ, all the columns were retrofitted along the entire height of the building. After the seismic retrofit, the size of the columns increased to 50x50 cm for L'Aquila, and 60x60 cm for Reggio Calabria. Concerning the low-damage external exoskeleton, the additional structural system was designed following the Displacement-Based Retrofit (DBR) procedure [26]. Such a procedure is the natural extension of the Direct Displacement-Based Design (DDBD) procedure proposed [26] for new buildings [27]. The main scope of the DBR procedure is to prevent the existing structure from reaching and exceeding its failure displacement profile, which can be assessed through the results of pushover analyses. To be consistent with the *Italian Building Code* [23], the displacement profile was defined as the one causing the attainment of the Life-Safety Limit State (LSLS, which also corresponds to DS3). The corresponding design drift θ_D , which is the input data of the DBR, was set to 1.00%, considering that the failure of the as-built structures is governed by the brittle failure of external beam-column joints [28] (further information is available in §3.2). In designing the exoskeleton, a re-centering ratio $\lambda=1.50$ was considered to ensure the self-centering capabilities of the retrofitted systems. For both cities, an external frame exoskeleton was considered, consisting of beams and columns of 50cm in height and 30cm in width. The main differences between the exoskeletons implemented in the two cities are related to the dimensions of *Plug&Play* dissipaters as well as to the diameter and post-tensioning forces of cables. Such differences in the reinforcement details allowed to meet the slightly different seismic demands in both locations.

3.2 Seismic performance and loss assessment

This paragraph deals with the definition of the seismic performance of the as-built and retrofitted configurations. Firstly, pushover analyses were carried out on the as-built structure. These analyses proved that the brittle failure of both external and internal beam-column joints mainly governs the failure. The results of the pushover analyses were used to define the Safety Index IS-V value (or %NBS) for both locations. More specifically, the as-built configuration scores 52% and 49% IS-V, for L'Aquila and Reggio Calabria, respectively. Moreover, the results of such analyses were used to drive the design of the retrofit alternatives. Fig. 5a compares the pushover curves of the as-built and retrofitted configurations for the case study located in L'Aquila. Additionally, to prove the self-centering capabilities of structures retrofitted using the external low-damage exoskeleton, cyclic non-linear static push-pull analyses were carried out, Fig. 5b.

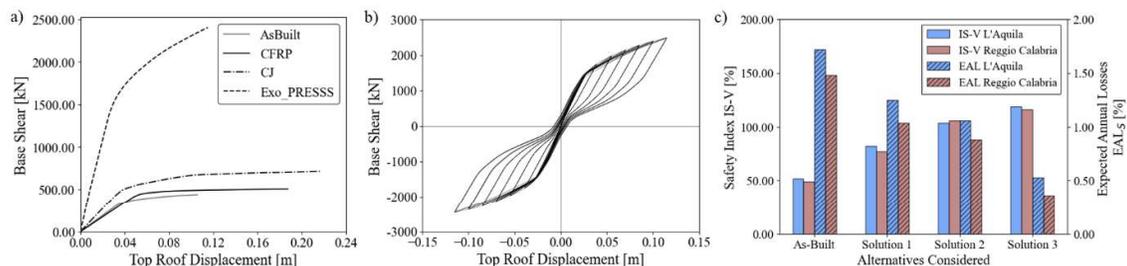


Fig. 5. a) Results in terms of pushover curves for the as-built structure and for all the retrofit alternatives for L'Aquila case study, b) push-pull analysis for the structure retrofitted using the low-damage exoskeleton, and c) Safety Index (IS-V or %NBS) and Expected Annual Losses (EALs) for all the alternative configurations and for both the considered locations.

As for the as-built structure, the IS-V (%NBS) was defined for all the retrofitted configurations. By using the CFRP, an IS-V value equal to 82% and 77% was achieved for L'Aquila and Reggio Calabria, respectively. It is worth noticing that for this specific case, such a technique does not allow to achieve a safety index equal to or greater than 100%, and even considering additional actions (e.g., increasing the number of columns subjected to the wrapping) a considerable increase of safety level could not be achieved. On the other hand, the implementation of the CJ allows to reach an IS-V equal to 104% for L'Aquila and 106% for Reggio Calabria. Finally, adopting the low-damage exoskeleton, the retrofitted

structures score 119% and 116% IS-V for L’Aquila and Reggio Calabria, respectively. All the IS-V values are summarized in Table 1, and illustrated in Fig. 5c.

Table 1. IS-V (%NBS) and EAL_S values for all alternatives and locations. N.B.: Aq stands for L’Aquila and RC for Reggio Calabria.

	IS-V Aq	IS-V RC	EAL _S Aq	EAL _S RC
As-built	52%	49%	1.72%	1.48%
CFRP	82%	77%	1.25%	1.04%
CJ	104%	106%	1.06%	0.88%
Exoskeleton	119%	116%	0.53%	0.36%

Moreover, the procedure outlined in §2.3 was implemented to define the EALs. For the as-built configurations, the associated seismic losses (i.e., EAL_S) are equal to 1.72% and 1.48% for L’Aquila and Reggio Calabria, respectively. By implementing the interventions based on CFRP the performance can be slightly improved by reducing the EAL_S, as its value decreases to 1.25% for L’Aquila and 1.04% for Reggio Calabria. The reduced improvement is mainly justified by the fact that, while the CFRP is useful for improving the level of safety by replacing the brittle shear failure mechanisms with more desirable flexural/ductile ones, it does not allow a considerable improvement of the structural stiffness. Indeed, strategies able to improve the structural stiffness, allow to provide better protection of drift-sensitive non-structural components, which are responsible for most of the losses in case of a seismic event [29]. This also justifies the better performances when the CJ technique is implemented. In case of CJ, the EAL_S moves to 1.06% and 0.88%, for L’Aquila and Reggio Calabria, respectively. Finally, considering the implementation of the external low-damage exoskeleton, the greatest reduction of expected losses was achieved, with EAL_S values of 0.53% for L’Aquila and 0.36% for Reggio Calabria. The EAL_S values are summarized in Table 1 and presented in Fig. 5c for the as-built and retrofitted configurations, and for both locations. Finally, it is worth mentioning that this study uses the damage-to-loss ratios presented in the national guidelines [19] to define the EAL_S. This consequence model does not enable to catch the higher performance of the low-damage PRESSS technology. Indeed, The DLRs reported in [19] were derived based on actual repairing costs observed in the aftermath of the 2009 L’Aquila earthquake (“White Book” [30]) for traditional monolithic buildings. For this reason, neither the actual lower repairing costs and time nor the beneficial effect of negligible/limited residual displacements of the low-damage PRESSS technology are considered in this study. Consequently, ongoing research efforts are aiming at assessing the benefits of using more refined, component-based, probabilistic procedures for the loss assessment (e.g., the one outlined in FEMA P-58, [31]).

3.3 Energy performance and loss assessment

Dynamic energy simulations were performed to define the energy consumption of the buildings, and consequently, the expected losses related to such consumption (i.e., EAL_E). Firstly, the energy simulations were carried out on the as-built configuration for both locations. Then, the analyses were repeated considering either the implementation of the thermal coat (used for the combined interventions of Solution 1 and 2), or the low-damage “double-skin” system (adopted for the integrated approach of Solution 3). Such analyses enables to quantify the hourly energy consumptions, which were elaborated to define the monthly energy consumptions related to each load (i.e., heating, cooling, hot water production, lighting, and electric equipment). From the energy results, it was observed the huge difference in terms of heating/cooling demand for the two locations, as a consequence of the different climatic conditions. On the other hand, energy consumption related to the remaining loads (i.e., hot water production, lighting, electric equipment) is constant throughout the year. Building on such results, the energy costs and consequently the EAL_E were finally assessed. All the results in terms of energy consumption, energy cost, EAL_E, and percentage of EAL_E reduction, are summarized in Table 2. In all the refurbished cases, it is found a considerable decrease in energy consumption, and consequently in the energy costs and related losses. More specifically, for all the building alternatives in L’Aquila, the EAL_E reduces by 0.86%. On the other hand, the EAL_E reduction for Reggio Calabria case study is equal to 1.59% for Solution 1 or 2, while is equal to 1.63% for Solution 3. For both locations, the reductions are quite similar for the

implemented solutions. This is due to the same U-values imposed by the DM 26/06 [11] and targeted for the renovation of the building envelope.

Table 2. Results of the energy simulations for the renovation alternatives and both locations. N.B.: Aq stands for L’Aquila and RC for Reggio Calabria.

	Consumption [kWh/m ²]	Cost [k€]	EAL _E [%]	EAL _E Reduction [%]
As-Built AQ/RC	220.38/196.87	22.69/37.10	1.13/2.82	---/---
Solution 1 AQ/RC	105.29/130.10	15.39/23.56	0.27/1.23	0.86/1.59
Solution 2 AQ/RC	105.29/130.10	15.39/23.56	0.27/1.23	0.86/1.59
Solution 3 AQ/RC	106.26/128.57	15.44/23.25	0.27/1.19	0.86/1.63

Finally, it is worth stressing that while the percentage reduction in terms of EAL_E is higher for Reggio Calabria, the other parameters (i.e., consumption, cost, and EAL_E) are higher than those observed for L’Aquila. This is a direct consequence of the higher costs of electricity for cooling load, which is predominant in the warm climate (i.e., Reggio Calabria). This also justifies the choice to adopt shading devices in the warm climate, in order to reduce energy consumption which otherwise would remain too high, as observed in a previous study by the authors [6].

3.4 Classification of the alternatives through a common Green and Resilient Indicator (GRI)

This section aims to prove the enhanced performance of buildings renovated using external exoskeletons equipped with high-performance double-skin systems compared to traditional, yet already integrated, solutions based on seismic local interventions and thermal coating. The combined seismic and energy performance is herein assessed through the Green and Resilient Indicator (GRI) introduced by Calvi *et al.* in 2016 [10]. This indicator enables to rank the alternatives based on both EAL_S and EAL_E, by defining a classification from A+ to F, where A+ is the best class (low loss) and F the worst one (high loss). Fig. 6a and b presents the results in terms of GRI for the as-built and retrofitted configurations, for L’Aquila and Reggio Calabria, respectively.

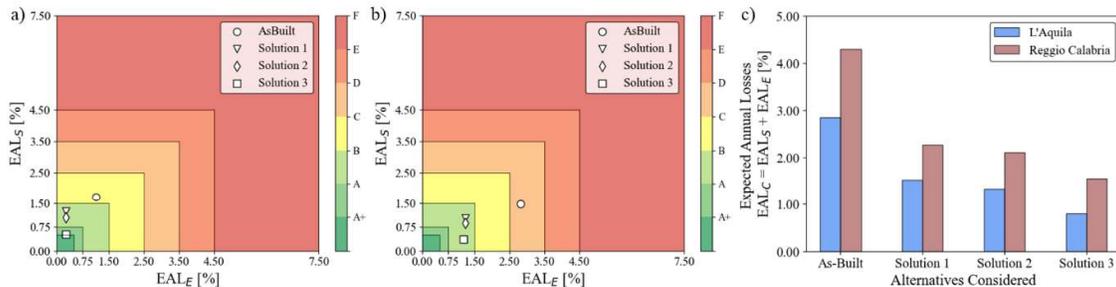


Fig. 6. GRI classification for the as-built configuration and the considered alternatives in a) L’Aquila and b) Reggio Calabria. c) Results in terms of combined losses EAL_C.

The as-built configuration is ranked as class C in L’Aquila and class D in Reggio Calabria. After the implementation of the renovation strategies, the reference building in L’Aquila moves to class B if the combined solutions are implemented (i.e., Solution 1 and 2), and to class A for the integrated exoskeleton-based intervention. On the other hand, for Reggio Calabria, the building moves from class D to B disregarding the implemented solution. Fig. 6a and b show that the solution based on the external exoskeleton is clearly superior, as the representative point is closer to the origin of the axis. Indeed, if the point is closer to the origin, it means that lower combined losses (i.e., $EAL_C = EAL_S + EAL_E$) are observed, Fig. 6c. More specifically, the EAL_C value is equal to 2.85% / 4.30% for L’Aquila / Reggio Calabria in the as-built configuration. For L’Aquila, such combined losses decrease to 1.52% for Solution 1, 1.33% for Solution 2, and 0.80% in the case of Solution 3. On the other hand, considering Reggio Calabria, the EAL_C values move to 2.27%, 2.11%, and 1.55% for Solution 1, 2, and 3, respectively. The

higher performance of Solution 3 is thus further confirmed by the EAL_C values, and from their reduction with respect to the as-built configuration. Indeed, in the case of L'Aquila it is possible to note a reduction of EAL_C equal to 1.33%, 1.52%, and 2.05% for Solution 1, 2, and 3, respectively. On the other hand, considering Reggio Calabria, such reductions are equal to 1.58%, 2.19%, and 2.75% for the three considered solutions. In both the locations it is thus easy to note that the higher reduction of the combined losses is related to Solution 3.

4 Conclusions

This paper investigated the efficiency and effectiveness of an integrated solution for the holistic (seismic + energy) renovation of the existing building stock. The solution is based on the implementation of a low-damage rocking-dissipative external exoskeleton equipped with high-performing “double-skin” facades for energy upgrading and architectural restyling. Its enhanced performance was discussed through a comparison with traditional technical solutions based on seismic local retrofit combined with thermal coating. The high potential of the exoskeleton solutions was demonstrated for a 5-storey reinforced concrete building located in two different cities with high seismic hazard. On the other hand, the two locations are characterized by different climatic conditions (i.e., a cold climate for L'Aquila, and a warm climate for Reggio Calabria). The enhanced performance of the exoskeleton was proved by defining a safety index (IS-V or %NBS) for all the retrofit alternatives. The results confirm that the exoskeleton provides better safety enhancement than the other local strategies for seismic upgrading (i.e., use of Carbon-Fiber Reinforced Polymers, CFRP; and implementation of the Concrete Jacketing, CJ). Moreover, by implementing non-linear dynamic time-history analysis, the Expected Annual Losses (EAL_S) were quantified following a probabilistic approach based on the definition of fragility and vulnerability curves. Even in this case, the reduction of losses for the exoskeleton solution was greater than those related to the implementation of conventional strategies (i.e., CFRP, CJ). Furthermore, dynamic energy analyses were conducted to define the energy consumption and associated economic losses (EAL_E). The outcomes of both the seismic and energy analyses were finally combined to define the integrated seismic/energy building performance of the alternatives in terms of combined losses (EAL_C) and Green and Resilient Indicator (GRI). Such indicators further proved the efficiency of the exoskeleton solution. In the case of L'Aquila, the building moves from a GRI class C to B when combined (local strengthening and thermal coating) strategies are implemented, while it moves from C to A with the exoskeleton. Concerning Reggio Calabria, each renovation alternative moves the GRI class from D to B. However, even if the same class is achieved, it is still possible to demonstrate the enhanced performance of the exoskeleton by considering the reduced value of the EAL_C compared to the other strategies. Despite very promising results, future developments are needed. For example, the adoption of a component-based loss assessment procedure should be used to catch the higher performance of low-damage technologies, thus more accurately evaluating the (even lower) seismic losses (EAL_S) associated to low-damage solutions. Moreover, ongoing research activities are focusing on using further resilience indicators to prove the efficiency of the proposed solution. Indeed, such indicators provide insights for better evaluating the preparedness of the building stock against extreme events related to earthquakes and weather-related ones, such as the more frequent heatwaves. Finally, it is worth noticing that based on the results obtained, the solution presented can represent a “step-change” for seismic risk reduction, and potentially for implementing national plans for the integrated rehabilitation of existing buildings [32].

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