# INTEGRATED ENERGY AND SEISMIC RETROFITTING OF URM BUILDINGS BASED ON AN ENVIRONMENTAL AND ECONOMIC COST

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**Abstract**: *The Spanish building stock is an ageing infrastructure that was built before the applications of seismic and energy codes. Hence, these buildings are characterised by both considerable seismic vulnerability and energy poverty. In order to improve their performance to ensure the seismic safety and the comfort conditions, the energy and seismic retrofitting are both needed. Generally, these have been carried out as sole interventions, despite the advantages of combined retrofitting (sustainability and money saving). Hence, in this work, the combined and integrated energy and seismic retrofitting of existing residential buildings in Spain is presented. The method has been applied to a case study unreinforced masonry building in Spain. This building is representative of a typical residential typology. The building has been proved to be vulnerable to the expected seismic demand of the area and it does not comply with the energy provisions in terms of comfort conditions and carbon emissions. To do so, the environmental impact and the economic costs of several integrated retrofitting solutions have been borne in mind. These solutions are specifically developed for the case study building to improve its in-plane behaviour (applied to the façade of the building). Several incremental dynamic analyses and the energy performance assessment have been carried out. The results showed that combined retrofitting is justified and beneficial instead of sole retrofitting interventions, which are currently applied in existing buildings. Also, it is concluded that, for the case study building, solutions focused on the improvement and strengthening of the walls have obtained better performance levels.*

## 1. Introduction

A major part of the European Union (EU) building stock is reaching its nominal life (Pohoryles et al., (2020). Apart from the ageing and the degrading of materials, a large amount of these buildings was mainly constructed with obsolete guidelines, before the application of design codes or with low economical and technical resources (Calama-González et al., (2022). This leads to a poor or inadequate energy performance of these buildings. In fact, the building sector consumes up to 40% of the total EU annual energy and produces 36% of the annual carbon emissions (European Commission, (2012). In addition, owing to the construction date, some of these structures, particularly those located in EU earthquake-prone areas, were not designed to withstand seismic demands. Consequently, their seismic safety is not warranted, as proved by the catastrophic effects of recent earthquakes suffered in the EU. In the case of Spain, the recent 2016 Lorca earthquake resulted in 40% of the neighbourhoods being severely or very severely damaged. This led to a significant number of injuries, as well as substantial repairing costs (Ruiz-Pinilla et al., (2016)).

Subsequently, it is considered that at least 65% of the EU building stock in seismic areas requires to be both energy and seismic retrofitted to comply with the minimum prescriptions (Instituto para la diversificación y ahorro de la energía (IDAE), (2011). Hence, in recent years, efforts have been focused on the seismic strengthening and the energy efficiency improvement of the existing building stock. One of the key actions developed is the EU Green Deal (European Parliament, (2019), approved to ensure EU climate neutrality by 2030 and 2050. Particularly, in Spain, the PRE5000 programme is focused on the energy refurbishment to reduce the energy consumption and the carbon emissions of the building stock. To do so, there are several energy rehabilitation activities recently funded by the EU-Next Generation programme and framed within the Spanish Recovery, Transformation and Resilience Plan. Nonetheless, the building refurbishment rate is still very low in the EU, reaching only a 2-3% (European Parliament, (2016).

Even though the core action of the retrofitting process seems to be the energy performance, the interaction with other aspects related to the building system should not be omitted (European Commission, (2019). In fact, at the retrofitting designing stage, the combination of energy, structural and environmental information can lead to more efficient interventions and the possibility of entailing additional economic and environmental benefits (attaining savings in the order of billions per year) as proved in recent works (Belleri and Marini, (2016); Filippova et al., (2018). By performing combined energy and seismic retrofitting, it is possible to develop sustainable practices that could result in a reduction of Caprino et al., (2021): i) the environmental impact, expressed in terms of energy consumption or carbon emissions of the buildings use and their retrofitting intervention; ii) the economic impact, related to the construction and maintenance costs, as well as the expected annual losses due to the energy and seismic demands; and, iii) the social risk, referring to the standard and comfort of living, the risk-awareness and energy poverty or the potential wounded/injured owing to hazardous events. However, many studies dealing with large-scale retrofit have focused deeply on single aspects, such as the mechanical improvement, while few works have dealt with the integration of the sustainable objectives based on the environmental, economic and social aspects (Romano, (2014).

Novel methodologies for approaching either the integrated design or for the selection of solutions bearing in mind technical and economic constraints are rather unexplored. Nevertheless, a few works can be found on the combined assessment, mainly based on developing feasible and novel solutions/systems or proposing frameworks for the analysis. In Menna et al., (2021), a conceptual design method was proposed for the combined assessment based on the improvement of the seismic and the energy performances. In Caruso et al., (2021), retrofitting interventions were mainly analysed as sole interventions. In addition, they were energetically and seismically combined but not integrated as one-shot interventions. In Pohoryles et al., (2020), an original approach was proposed to account for the combined losses because of energy and seismic retrofitting based on the expected annual losses. A large-scale method was proposed, including a variety of EU residential building typologies at different locations. This study expanded previous works by assessing the benefits of combined retrofitting. Furthermore, a combined retrofitting scheme was tested based on the addition of thermal insulation and a composite material applied to the building envelope.

In this work, as a preliminary study, integrated seismic strengthening and energy efficiency improvement retrofitting solutions have been assessed through a proposed combined framework. The goal has been designing and analysing one-shot interventions that can help to reduce economic costs, while retaining acceptable performance targets. The framework proposed has been based on several decision variables that enable a combined assessment from the environmental, the economic and the performance points of view. These have been the savings from the expected annual losses derived from the energy and the seismic retrofitting (both in economic costs and carbon emissions), the combined economic cost and the payback period (PB). This last concept has been recently proposed in the literature for the combined assessment and it is computed according to the expected annual losses owing to energy and seismic risks of single or combined actions. The solutions and the framework have been applied to a case study building located in Seville, in southern Spain. This is one of the most seismic hazardous areas of the Iberian Peninsula. Furthermore, the building is an old archetype unreinforced masonry (URM) building that belongs to a typical Spanish neighbourhood. It does not comply with the current seismic safety criteria; it does not meet the standard levels of comfort and it is characterised by high levels of energy poverty and carbon emissions. Integrated retrofitting solutions have been designed based on the enhancement of the behaviour of the façades, which is the weakest part of the system.

## 2. Case study

A significant part of the Spanish building stock was constructed prior to the first energy and seismic codes, which were initially introduced in the 1970s. In the case of old URM buildings, these were mainly built during the 1960s and they represent almost 30% of the Spanish residential stock Requena-García-Cruz et al., (2023). Most of them lack thermal insulation and present unsuitable windows and frames, among others. This results in a poor energy performance because of their significant energy consumption and carbon emissions. Furthermore, these URM buildings are characterised by a high seismic vulnerability due to their aseismic design, the degradation of the materials and the poor quality of the mechanical parameters. In this work, the building selected as the case study is representative of a typical linear typology of residential URM buildings dating from the 60s, located in Seville (Spain) (Figure 1).

*Figure 1. Structural configuration, pointing out in red the interior RC frame and beams and in blue the masonry walls. Distribution in elevation and in plan. Plans and photo of the building by the authors.*

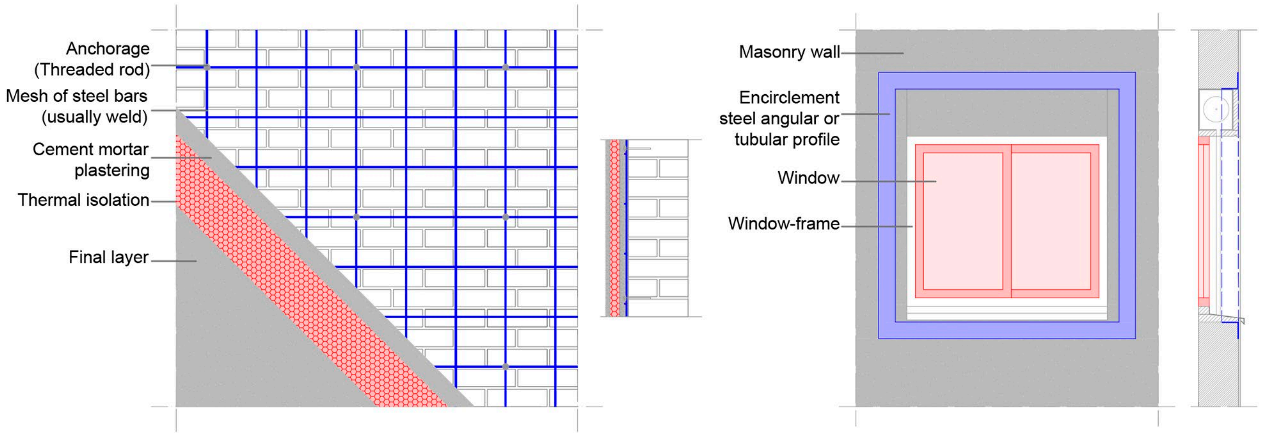
### 2.2. Structural and constructive characterisation

The building presents a mixed structural configuration: URM walls in the perimeter, a single interior reinforced concrete (RC) frame and RC ribbed slabs with a narrow RC ring beam, pre-cast joists and ceramic vaults. It is a five-storey structure whose walls vary according to height: at ground floor, they are composed of solid ceramic bricks of 0.34 m of thickness; and, in the rest of the floors, they are made of 0.28 m of hollow ceramic bricks. The box-like behaviour is guaranteed due to its sufficient horizontal connections. The mechanical parameters have been defined according to Requena-García-Cruz et al., (2023). The masonry compressive strength ($f_c$), the elastic ($E$) and the shear moduli ($G$) are 4.0 MPa, 1200 MPa and 150 GPa, respectively. The diagonal cracking strength ($\tau_0$) has been set as 0.05 MPa. For the RC, $f_c$, $E$ and $G$ are 25.5 MPa, 3000 GPa and 17000 GPa, respectively. For the rebar steel, the yielding strength ($f_y$), $E$ and $G$ are 428 MPa, 210 GPa and 800 GPa, respectively.

The configuration of the envelope of the building is the typical one that can be found in buildings constructed during the 60s-70s in southern Spain. It is characterised by the absence of thermal insulation and the presence of several thermal bridges. The envelope presents a transmittance (U) of 1.74 W/m$^2$K and it is built with cement mortar (2 cm), ceramic bricks (24 cm) and two layers of plaster (1+1 cm). The floor slabs (U=1.57 W/m$^2$K) are composed of terrazzo floor (2 cm) with cement mortar (3 cm) and 25 cm RC ribbed slab. The roof (U=1.59 W/m$^2$K) is distinguished by a layer of lightweight aggregate concrete for the formation of the slope (of around 5 cm); RC ribbed slab (25 cm) and plaster (1.5 cm). The openings are designed with sliding type windows, steel frames without thermal breaks and single glazing with an exterior roller shutter (U=5.70 W/m$^2$K). Further information on the structural and constructive characteristics of the building can be found in a previous work carried out by the authors (Requena-Garcia-Cruz *et al.*, 2022).

### 2.3. Integrated retrofitting techniques considered

The retrofitting techniques have been considered based on the as-built behaviour of the building and the results previously obtained in Requena-Garcia-Cruz *et al.*, (2022). As seen, the case study building is expected to present an in-plane failure of most of the URM panels on the ground floor and some piers. It is also observed that the façades of the building lead to high ratios of heating transfer. Considering these results, the retrofitting techniques have been applied to improve the behaviour of the walls and the elements of the façade. Two retrofitting packages have been considered to better the behaviour of openings/windows (W) and walls/façades (F). Their conceptual designs are shown in Figure 2. Furthermore, as concluded by the literature, these are the retrofitting strategies that have led to higher performances ratios. Also, they are more suitable for the case study building analysed, given the weakest elements obtained. Later, these solutions have been integrated to assess their combined effect. The first technique, W, has been based on the addition of encirclements to improve the seismic behaviour and the replacement/enhancement of windows (both glazing and frames) to improve the building's energy performance. The second technique, F, has focused on the addition of steel grids and thermal insulation on URM walls to improve the seismic and the energy performance, respectively.



a) b)

*Figure 2. Conceptual design of the retrofitting solutions considered. a) F, walls strengthening and addition of thermal insulation; b) W, addition of encirclements and windows replacement/enhancement.*

The solutions selected to be analysed in this work have been those that presented the best benefit-cost ratio in the previous work of the authors. This ratio bore in mind the energy (E), the seismic (S) performance and the construction costs. For the improvement of the windows, the solutions considered have been: S-W8, which added the lowest section of O-profiles in the openings, O-profile 60.2 and steel yielding strength ($f_y$) of 235 MPa; and E-W1, which used aluminium frames with a thermal bridge break (U =2.8 W/m$^2$K) and standard 4/6/4 double glazing of U=2.5 W/m$^2$K. For the improvement of the walls, the solutions selected have been: S-F8, which added the highest amount of retrofitting steel, grids of 15 cm of spacing, 8 mm of diameter and $f_y$=275 MPa; and E-F2, which added the highest amount of thermal insulation, 10 cm expanded polystyrene styroboard (EPS) of U=0.037 W/m$^2$K (U=0.31 W/m$^2$K).

## 3. Method

### 3.1. Integrated retrofitting method proposed

In this work, a set of different decision variables (DV) have been encompassed for the combined assessment of the retrofitting solutions based on the environmental, the economic and the performance points of view. The DVs considered in this work have been: the savings from the expected annual losses derived from the energy ($\Delta EAL_E$) and the seismic ($\Delta EAL_S$) retrofitting, the combined economic cost (C) and the PB.

The savings due to the retrofitting (r) have been computed as the difference between the initial (i) annual losses and the losses after the retrofitting, being $\Delta EAL = EAL_i - EAL_r$ (Pohoryles *et al.*, 2020). $EAL_E$ have been computed as the ratio between the annual energy cost (considering both the heating and the cooling demand) and the total building value (Eq.(1)). They have been obtained in both economic (€) and carbon emissions (kgCO$_2$) costs. As well known, the electricity market has varied considerably in the last few years. In this work, an analysis concerning the electricity price trend and forecast in Spain has been carried out to obtain an expected price of the electricity with taxes (€/kWh). Data have been obtained from Datosmacro, (2023) and are shown in Figure 3. The $EAL_S$ have been obtained as the ratio of the seismic losses (obtained by integrating the vulnerability curve obtained at different intensities over the seismic hazard curve at the site and the replacement cost of the building (Eq.(2)).

$$EAL_E = \frac{annual\ heating + cooling\ cost}{replacement\ building\ cost} = \frac{annual\ energy\ cost}{replacement\ building\ cost}\ (\%) \qquad (1)$$

$$EAL_S = \frac{seismic\ losses}{replacement\ building\ cost}\ (\%) \qquad (2)$$

The retrofit costs have been computed according to a Spanish construction cost database (CYPE Ingenieros S.A., n.d.). The cost of the integrated interventions has been estimated to be 25% cheaper than the energy and the seismic retrofitting carried out as sole interventions, similarly to Pohoryles *et al.*, (2020). This is due to the reduction of the labour and indirect costs provided by one-action interventions. The replacement cost of the building has been evaluated by multiplying the total floor area by an average construction cost per area (Table 1). This datum has been defined according to a Spanish database and the type of structure (Official College of Architects of Seville [Colegio Oficial de Arquitectos de Sevilla], 2023). The replacement cost of the building must take into account the cost of demolishing and the removal of debris. Therefore, the price corresponding to the construction of new buildings has been increased up to 30% (Caruso *et al.*, 2019).

*Table 1. Replacement cost of the case study building.*

| **Parameter** | **Value** |
|---|---|
| Nº of slabs | 5 |
| Dimensions | 21.70 x 8.20 m, 178 m$^2$ |
| Total area | 890 m$^2$ |
| Cost per m$^2$ | 708 €/m$^2$ x 30%, 920.40 €/m$^2$ |
| Replacement cost | 819,156 € |

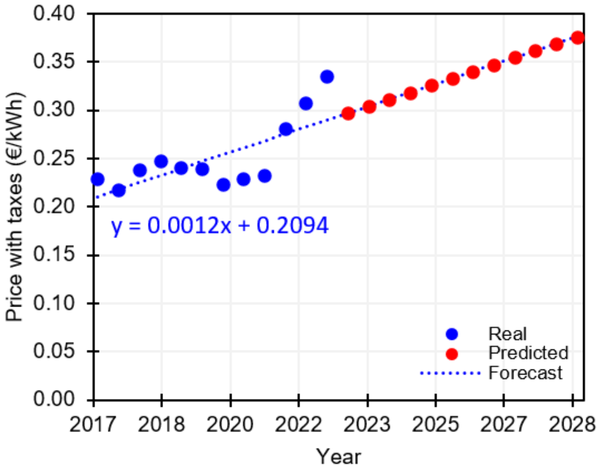


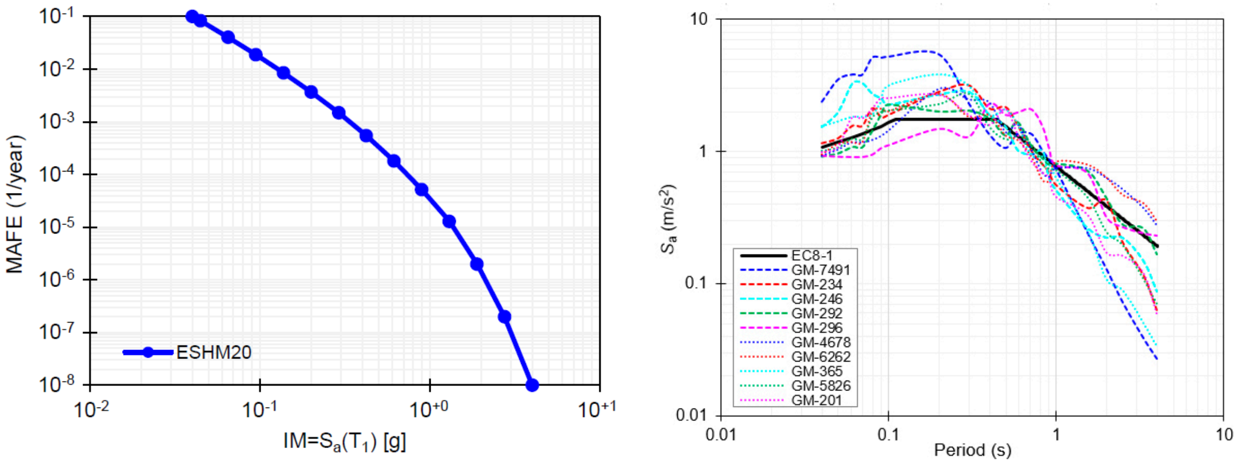
Figure 3. Electricity price trend and forecast in Spain.

The PB of the retrofitting solutions has been also computed as the ratio of the costs of the retrofitting and the annual cost savings (Eq.(3)). The retrofitting costs have been expressed with reference to the replacement cost of the non-retrofitting building. k refers to the type of evaluation, corresponding to the values of the combined savings or just those from the energy and the seismic retrofitting as sole interventions.

$$PB_{period} = \frac{retrofitting\ cost_k / replacement\ building\ cost}{\Delta EAL_k} \qquad (3)$$

### 3.2. Seismic assessment

In order to compute the seismic expected losses, works are generally based on the performance-based earthquake engineering method from the Pacific Earthquake Engineering Research (PEER-PBEE) framework. The PEER–PBEE procedure is based on the hazard, the structural, the damage and the loss analyses. In this work, the PEER PACT (Federal Emergency Management Agency (FEMA), 2012) software has been used to calculate the EALs. For the hazard analysis, the annual probability of exceedance (PE) of the peak ground acceleration (PGA) is computed according to the seismic hazard of the region. In this case, the PGA of Seville is 0.09g, which corresponds to a PE of 10% in 50 years, resulting in a return period of 475 years. The mean annual frequency of exceedance (MAFE) and the seismic hazard curve at the site has been computed from (European Facilities for Earthquake Hazard and Risk (EFEHR), 2021) for the location of Seville (Figure 4(a)). The spectral acceleration ($S_A$) response spectrum has been constructed according to the Eurocode 8-Part 1 (EC8-1) (European Union, 2004), considering a soil type C. For the structural assessment, the engineering demand parameters (EDP) (interstorey-drift ratio (IDR) and peak floor acceleration (PFA)) have been defined through incremental dynamic analyses (IDA) performed in OpenSees (McKenna *et al.*, 2000) at different intensity measures (IM). In total, 5 levels of IM have been considered and a set of 11 pairs of real ground motions (GM) have been selected, as recommended by FEMA P-58 (Federal Emergency Management Agency (FEMA), 2018) (Figure 4(b)). The method proposed by (Morales-Esteban *et al.*, 2012) has been used to select the GM that best fit the $S_A$-based response spectrum. Real GM from the European Strong motion database have been used.



a) b)

*Figure 4. (a) Seismic hazard curve at the site; (b) GM selected for the IDA.*

3D nonlinear numerical models have been developed within the OpenSees framework and the STKO pre/post processor (Petracca *et al.*, 2017). The equivalent frame (EF) method that idealises URM panels as piers and spandrels has been followed (Lagomarsino *et al.*, 2013). EF macro-elements have been defined for the URM piers and spandrels by defining force-beam elements and following the distributed plasticity approach as presented in Raka *et al.*, (2015); Sepe *et al.*, (2014). The masonry nonlinear behaviour has been accounted for by means of the strain-stress uniaxial material 'Concrete02' as in Camata *et al.*, (2022). A phenomenological shear force-deformation ($V$-$\gamma$) law has been defined according to the procedure defined in (Raka *et al.*, 2015) to account for shear behaviour. The Turnšek and Čačovič criterion (Turnšek and Čačovič, 1971) has been used to define the ultimate shear force ($V_y$). Since in OpenSees the axial load ($N$) acting on URM panels is not updated automatically, it is assumed that $N$ is set as equal to the initial gravitational loads. Damage and collapse in URM structures can be either due to the in- or out-of-plane failure (Sorrentino *et al.*, 2019). In this case, since the box-like behaviour is guaranteed, only the in-plane behaviour has been assessed. RC elements have been modelled as force-beam elements following the distributed plasticity approach and using 'Concrete02'.

### 3.3. Energy and environmental impact assessment

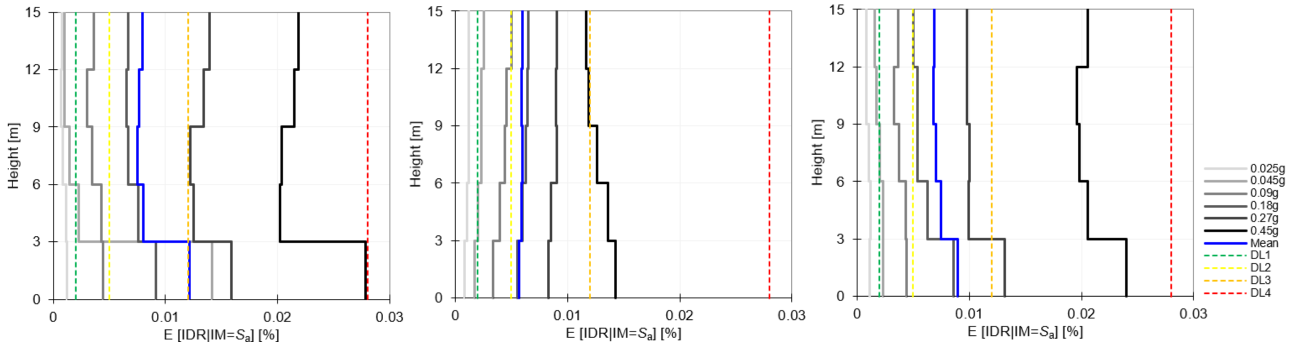
A building energy model has been constructed in the open access EnergyPlus v.9.2 simulation engine (National Renewable Energy Laboratory (NREL), 2023), to assess the thermal and energy performance of the case study under both as-built and retrofitted scenarios. As explained in 2.3, S-W8 considers windows replacement by energy-efficiency ones; and S-F8 includes thermal insulation to the façades. The energy model has been defined according to the building morphology, constructive and physical characteristics described in 2.2. Likewise, use patterns, lighting and equipment loads have been included following the criteria of the Spanish Technical Building Code (Spanish Ministry of Public Works [Ministerio de Fomento de España], 2009).

Heating and cooling energy demand, as well as heating and cooling energy consumption, have been obtained on an annual basis, considering kWh per built m². To do so, an electric heat pump system with indoor units has been included in the three cases (initial and retrofitted cases). This system is typically used for social retrofitting strategies as an active air conditioning solution implemented in a Mediterranean climate. The heating coefficient of performance (COP) and cooling energy efficiency ratio (EER) considered have been 3.40 and 3.00, respectively. Also, an environmental impact assessment has been carried out, reporting results on $CO_2$ emissions, due to the heating and cooling energy consumption of the building, for all the scenarios.

## 4. Results

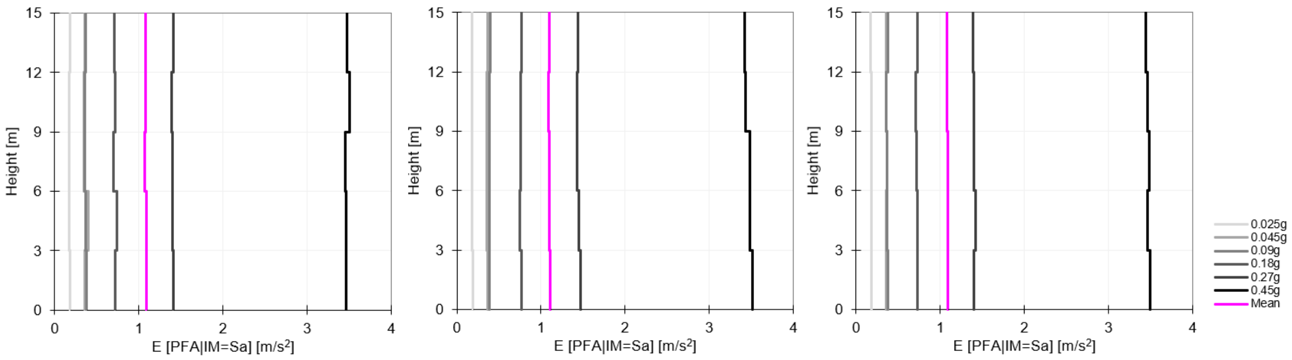
### 4.1. Seismic performance and loss assessment

In Figure 5, the results obtained from the IDA in terms of IDR have been plotted for the three scenarios considered. In addition, the IDR for the performance damage limits (DL) of old URM buildings (pre-code) have been plotted following the prescriptions established in (Federal Emergency Management Agency (FEMA), 2018). As can be observed, for the IM corresponding to the PGA of Seville, the IDR expected is located between DL2-DL3, meaning that the building might not comply with the seismic safety requirements. Also, as concluded in the previous work by the authors, URM panels on the ground floor could be severely damaged, reaching DL3. This is related to the irregularities in the façade of the building due to the creation of new openings over time. For the S-F8 retrofitting solution, the IDR decreases compared to the unretrofitted situation up to 36% on the ground floor. The decrease of the IDR for the rest of the storeys ranges between 7% and 14%. Damage is expected to be lower, being close to DL2. In the case of the S-F8 retrofitting solution, the IDR decreases much more than the previous solution: up to 114% on the ground floor and up to 26%-37% on the rest of the storeys. As observed, this is the retrofitting solution that leads to a non-observed/light damage for the PGA of Seville. In Figure 6, the PFA obtained from the IDA have been plotted for the three scenarios. As observed, no significant differences are expected for the cases considered: unretrofitted, S-F8 and S-W8.



a) b) c)

*Figure 5. Average IDR at the centre of masses for the cases considered: (a) unretrofitted; (b) S-F8; (c) S-W8.*

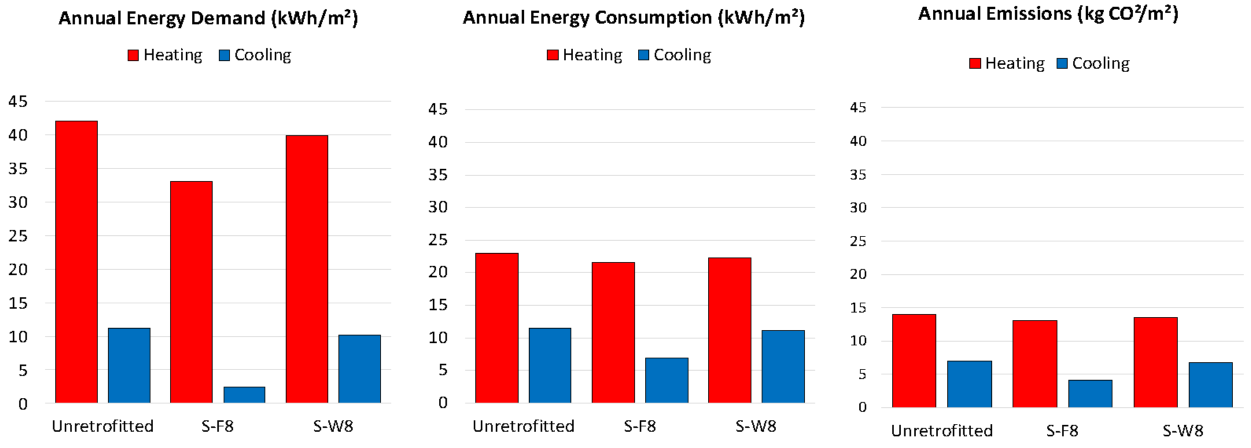


a) b) c)

*Figure 6. Average PFA at the centre of masses for the cases considered: (a) unretrofitted (b) S-F8 (c) S-W8.*

### 4.2. Energy and environmental performance

Figure 7 presents a comparison of the energy demand, energy consumption and $CO_2$ emissions reported for the three cases: unretrofitted, window replacement (S-W8) and thermal insulation in the façade (S-F8). It can be seen that heating demand is quite significant in all cases, with values up to 4 to 13 times higher than cooling demand. S-F8 strategy allows a noticeable reduction in heating demand of almost 9 kWh/m$^2$, while the impact of the window replacement S-W8 has a lower influence with only a 2 kWh/m$^2$ reduction, perhaps due to the existing cantilevers. Regarding cooling demand, S-F8 clearly presents the best performance with close to a 80 % reduction, when compared to the as-built case, while the S-W8 saves less than 1 kWh/m$^2$ energy cooling demand. This energy behaviour is similarly repeated when energy consumption and emissions are analysed. Heating consumption values are quite similar in all the scenarios, with barely significant differences, especially since only passive retrofit strategies are applied. Yet, important differences may be observed for cooling consumption, S-F8 being the solution that reports the lowest energy consumption and, subsequently, the lowest emissions.



a) b) c)

*Figure 7. Average total annual values in kWh/m$^2$ for heating (red) and cooling (blue): (a) energy demand (b) energy consumption and (c) $CO_2$ emissions, for the unretrofitted and retrofitted scenarios.*

### 4.3. Integrated retrofitting

In Table 2, the ΔEAL from the energy and the seismic retrofitting (considering the price of electricity in carbon emissions and in economic cost), the economic cost of the installation and the PBs of the combined solutions are presented. As can be observed, the solutions focused on the strengthening of the façades have obtained better results than those just centred on the improvement/replacement of openings and windows. A combined seismic and energy retrofitting of the walls (F-solutions) leads to a PB of almost one year. However, combined solutions concentrated on the improvement/replacement of windows and openings have obtained a PB of 2.81 years. This is owing to the higher installation costs and the lower values of savings from the seismic and energy retrofitting. In fact, a minimum percentage of savings from the energy retrofitting has been obtained, which can be related to the small size of the openings in the building. A combined action focused on the improvement of both aspects (the façades and the openings) results in a PB of 1.39 years. The improvement of the energy performance has been higher than the one obtained in the previous cases. The savings from the seismic retrofitting have also been higher. Hence, for an increase of the installation cost, considerably better results can be obtained.

*Table 2. Savings from the expected annual losses derived from the energy and the seismic retrofitting, economic cost and PB as combined interventions.*

| **Solution** | **$\Delta EAL_E$ [%, kgCO2]** | **$\Delta EAL_E$ [%, €]** | **$\Delta EAL_S$ [%]** | **C [€]** | **PB [years]** |
|---|---|---|---|---|---|
| S-F8+E-F2 | 0.44 | 0.18 | 15.88 | 122,830 | 0.93 |
| S-W8+E-W1 | 0.22 | 0.09 | 7.33 | 170,629 | 2.81 |
| S-W8+E-W1+S-F8+E-F2 | 0.57 | 0.18 | 20.50 | 252,375 | 1.39 |

In Table 3, the ΔEAL derived from the energy and the seismic retrofitting, the economic cost and the PB from the retrofitting of the building as sole actions are presented. However, as seen in Table 3, solutions installed as sole interventions lead to worse performance levels compared to the combined retrofitting. In fact, solutions focused on the seismic strengthening present lower PB values than those obtained from the combined assessment. Nevertheless, the worst performance levels have been obtained for the energy retrofitting. As seen, the energy retrofitting solutions as sole interventions lead to significantly higher values of PBs than those obtained for the combined assessment.

*Table 3. Savings from the expected annual losses derived from the energy and the seismic retrofitting, economic cost and PB as sole interventions.*

| **Solution** | **$\Delta EAL_E$ [%]** | **$\Delta EAL_S$ [%]** | **C [€]** | **PB [years]** |
|---|---|---|---|---|
| S-F8 |  | 15.88 | 86,119 | 0.66 |
| S-W8 |  | 7.33 | 155,730 | 2.60 |
| E-F2 | 0.18 |  | 58,386 | 38.65 |
| E-W1 | 0.09 |  | 45,000 | 59.59 |

## 5. Conclusions

In this work, integrated seismic strengthening and energy efficiency improvement retrofitting solutions have been assessed through a proposed combined framework. This has been based on several decision variables that enable a combined assessment from the environmental, the economic and the performance points of view. These have been the savings (in carbon emissions and economic cost) from the expected annual losses derived from the energy and the seismic retrofitting, the combined economic cost and the PB.

The results have shown that the solutions focused on the strengthening of the façades have obtained better results of ΔEALS than those just centred on the improvement/replacement of openings and windows. Focusing only on the PB, this has been 0.93 and 2.81 for each solution, respectively. This is because of the higher installation costs and the lower values of savings from the seismic and energy retrofitting obtained for the improvement/replacement of windows. In fact, a minimum percentage of savings from the energy retrofitting has been obtained, which can be related to the small size of the openings in the building. Higher percentages of savings of ΔEALS have been obtained if the building is seismically retrofitted compared to the energy retrofitting. This shows that, for this case, the seismic behaviour is worse than the energy performance. Compared to the results obtained as sole interventions, higher values of PBs have been obtained. Hence, it can be concluded that combined and integrated seismic and energy retrofitting of this building presents better performance levels. Even a combined seismic and energy retrofitting of both the façade elements and windows have led to better results in PB terms (1.39 years) and savings from the expected annual losses. Despite being more expensive, considerably better results can be obtained if a combined and integrated seismic and energy retrofitting is carried out in this building.

## 6. Acknowledgements

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