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Combined retrofit solutions for seismic resilience and energy efficiency of reinforced concrete residential buildings with infill walls

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ABSTRACT
The buildings built after the Second World War in Italy represent about 50% of the total building stock, their structures typically consisting of Reinforced Concrete (RC) frames with masonry infill walls. After a service life of about 50-60 years they inherently show structural/seismic and energy inadequacies – even more so when compared to current codes/standards – but their long-term maintenance and rehabilitation is often considered too complex and economically unsustainable. This paper presents a general framework and methodology to a) assess, through common quantitative indicators, and b) enhance the seismic and energetic performance of existing RC buildings.
The suggested methodology and approach is then applied - through the assessment and retrofit phases – to an Italian residential case study building. Often the refurbishment process of existing buildings (in particular in the private, residential and multi-family use) is limited to architectonical features or systems, with little or no coordination with, or consideration for, structural/seismic safety and energy/environmental efficiency.
For the above reasons, the proposed combined interventions will address the building system as a whole, thus including: structural, non-structural and HAVC components. Structural retrofit techniques designed to increase the safety index (IS-V) will, in this case study examples, include: Fiber Reinforced Polymers (FRP), Haunch Retrofit Solution (HRS), and external rocking-dissipative (PRESSS technology) wall. The masonry infills and roof elements represents key common targets between the two different objectives, i.e. enhancement of the seismic safety and of the energy efficiency. The non-structural elements will in fact be updated by combining capacity techniques to improve the strength and/or deformation/ductility capacity (e.g. Fiber Reinforced Clay Masonry, disconnection from the RC framework) with interventions aiming at reducing the thermal dispersion of the envelopes (e.g. thermal coats, insufflation of insulating material, cladding system). As one step further, towards a "passive" or zero-energy building, the HAVC systems will also be updated/improved with alternative solutions.
The overall effectiveness and the financial feasibility of alternative combined energy and seismic retrofitting solutions will be evaluated and compared by adopting a common approach and indicator, based on the evaluation of the Expected Annual Loss, EAL, i.e. in terms of either consumed energy and expected seismic losses).

1 INTRODUCTION

The high needs for housing and the speculation during the so called "economic boom", together with inadequate seismic design codes related, as well lack of rational usage of energy, have led to a built environment that is not satisfactory anymore according to nowadays standards and performance expectations. When also considering the natural material degradation and the general lack of regular maintenance, it is evident the need for a widespread integrated (energy efficiency, architectural, structural/seismic) rehabilitation intervention at national level.

To assess building sustainability, as commonly intended, or, in more specific terms, the ecological footprint, numerous factors in addition to the energy consumption needs to be considered. Life Cycle Analysis (LCA) is a method to analyse the environmental impact of a product (in this case a building) from cradle to grave (or to gate), i.e. from the extraction of raw material to the transportation, construction, use and disposal.

From this point of view, the enhancement of seismic safety and reduction of expected damage offered by a rehabilitation-retrofit intervention on structural and non-structural components - including the preservation and reuse of components due to change of use, performance upgrading, is of paramount importance, since lengthening the service life of materials, components and buildings is about controlling and slowing down their decay process. During the design of a building, specific attention should be paid to details that will influence the service life and maintenance of building parts (van Bueren et al. 2012).

As stated by different scientists, in order to be considered a realistic sustainability evaluation tool, LCA should develop and consider social (Social Life Cycle Assessment, SLCA) and economic aspects (Life Cycle Costing. LCC) to fulfil the concept of sustainability as described for example by (Mansour, 2014) in his Triple Bottom Line literature review.

Until now, environmental efficiency and hazard safety principles have typically been developed separately, despite influencing each other and both aiming at a better built environment, although with different objectives. In the past years, several methods to assess building sustainability started to take into account seismic safety and its positive impact on environmental, social and economic aspects. The contribution of seismic engineering to sustainability started to be acknowledged not just in terms of materials (direct influence) but also in terms of "protection" and damage control of the building (structural and) non-structural components and contents (indirect influence) which are responsible of the main construction and running costs, over indoor comfort and use of resources in a wider view.

Calvi, (2012, 2013) and co-authors (Calvi et al. 2016) proposed a simplified method for the seismic and energetic classification of buildings by a single parameter/indicator, referred to as Green and Resilience Indicator (GRI). The latter is based on the evaluation, and combination, of the Expected Annual Losses for both seismic events (EAL_S) and energetic consumptions (EAL_E), thus providing a common financial decision-making variable.

A further development on LCA and SPBA (Simplified Performance-Based Assessment) has been proposed by the Joint Research Centre in Ispra, Italy (Munafò and Tombolini, 2014; Munafò, 2017) The methodology is based on a building design method named Sustainable Structural Design (SSD) and consist of a sustainability analysis in the form of an LCA and an energy assessment followed by a simplified performance based structural analysis. Since the results of these analyses are given in different units (Kwh, CO_2tons, €) the final step is to quantify all aspects in monetary terms providing an economic parameter which could include upfront costs energy consumption, CO_2 emissions and earthquake losses. Menna et al. (2013) highlighted the importance of a common approach of earthquake engineering and sustainable design, considering that an energetic renovation affects significantly the LCA and economic losses when not coupled with a proper seismic retrofit/design. In a following study (Mauro et al. 2017) a multi-step approach is introduced: cost-optimal energy retrofit solutions are addressed via genetic algorithms, then expected economic losses due to seismic damage are assessed throughout the building lifecycle.

The methodology herein proposed is based on "common" (yet based on most recent and advanced procedures) evaluation and design processes, typical of structural engineering and building physics. The designer, depending on the level of accuracy and the design stage, performs in parallel an energetic and a structural assessment analysis to evaluate the expected individual performances. The novelty of the proposed approach relies on the selection and development on a (set of) integrated retrofit solution(s), based on the analysis of the combined effect and the mutual influence of the two aspects and objectives.

2 SEISMIC-ENERGETIC ASSESSMENT

2.1 Seismic Assessment

The seismic assessment methodology has been developed based on a Displacement-Based Seismic Assessment of Reinforced Concrete buildings (Priestley, 1997) integrated with the methodology for seismic risk classification introduced by the Italian law (D.M. n°65, 2017) to support the Sisma-Bonus (financial incentives for retrofitting existing buildings).

The proposed vulnerability assessment is based on the SLaMA method (Simple Lateral Mechanism Analysis) (NZSEE2017 - The Seismic Assessment of Existing Buildings), adapted to the requirements of the NTC 2018. Beam and column capacities have been calculated considering cracked sections for different axial load levels using CUMBIA (Montejo and Kowalsky, 2007), which can provide the moment-curvature analysis, actual and idealized (bilinear) force-displacement response, and axial load-moment interaction. The hierarchy of strength and the probable collapse sequence, with a focus to the beam-column joints, has been evaluated within M-N performance domain (Pampanin et al. 2002); the capacity of the external infill walls has been modelled with equivalent struts (Decanini et al. 1993; Crisafulli, 1997; Magenes et al. 2004). To better understand the interaction between the behaviour of various components and the sequence of local mechanisms, a numerical pushover analysis based on lumped plasticity models has been carried out.

The seismic hazard is defined according to Italian Code (NTC, 2018), which provides (for a given site, soil type and building class use) acceleration spectra for each limit state. Acceleration Displacement Response Spectra (ADRS) have been derived to compare capacity and demand through the Capacity Spectrum Method (Freeman, 1998; Fajfar, 1999).

The seismic Risk Classification is based on the combination of a Safety Index IS-V defined as the capacity/demand ratio at Life Safety limit state (SLV), as well as of the Expected Annual Losses, EAL_S, (in Italian referred to as PAM, Perdita Annua Media) to take into account the various performance under different intensity levels and limit states. The Risk Class for a building under analysis will be identified as the lower of the risk classes determined based on the IS-V assessment and on the PAM assessment.

The IS-V is expressed in terms of the Peak Ground Acceleration capacity, PGA_C, with reference to the soil condition of the building site, which induces the achievement of four limit states PGA_C (SLi) as specified by the NTC08, namely: 1) operational, SLO; 2) damage Control, SLD; 3) life safety SLV; 4) collapse prevention . The demand is defined in terms of elastic spectra anchored to various levels of Peak Ground Acceleration, PGA_D, for the building site, with reference to the same above-mentioned limit states SLi. The safety index IS-V is the ratio between the capacity of the building and the demand of a new building, expressed in terms of PGA_C and PGA_D, and referred to the life safety limit state, SLV.

Peculiarity and novelty of the Italian Guidelines is the introduction of the Expected Annual Losses, EAL, or PAM (Perdita Annua Media), a parameter widely adopted in the international literature for the evaluation of direct losses, (Cornell et al. 2000) to supplement and complement the information provided by the IS-V Safety Index, based primarily on Life Safety considerations, particularly when evaluating and comparing the benefits of alternative retrofit options (Beetham, 2013; Pampanin, 2017; Ligabue et al. 2018).

2.2 Energetic Assessment

In the built environment, buildings, both residential and commercial, are the largest energy consumers. They are then a key contributor to climate change and sustainability. Studies carried out by different national energy research institutes, namely ENEA in Italy and the Department of Energy, DOE, in USA, report that buildings energy consumption is around 40% of the total in "developed countries" (DOE, 2018; ENEA, 2019).

The Operational energy is a major part of the whole building consumption and, although it depends on different factors (allocated uses, envelope, HVAC systems, thermal settings and comfort preferences), is mostly regulated by the envelope. Therefore informed and conscious design choices are needed towards building sustainability (Konstantinou, 2015).

The Operational energy can be estimated using three analysis methods, depending on the required level of accuracy: stationary, quasi stationary, dynamic. The energy performance of the residential buildings and the potential energy savings after refurbishment toward the nearly-zero energy target. The calculation is realized by means of a quasi-steady state method based on the standard (UNI EN ISO 13790, 2008) and implemented in the Italian technical specification (UNI TS 11300, 2008). The building is an open system in which there is material and mono dimensional energy exchange between interior and exterior, it considers outside temperatures monthly means. Indoor temperature is set by law, depending on the use of the building, while external temperature is defined based on statistical measurement at the site.

According to (ISO 52000-1, 2017) the Energy Performance (EP) corresponds to the building global primary energy ($EP_{,gl}$) divided by the conditioned floor area. The global primary energy takes into account the energy demand to satisfy all the user's needs concerning heating (H), cooling (C), ventilation (V) and domestic hot water (W). These conversion factors are specified at national level and they distinguish the renewable energy part from the non-renewable one. Thus, the EP can be expressed either as the non-renewable primary energy (EP_{nren}) or as the total (non-renewable plus renewable) primary energy (EP_{tot}). These couple of indicators, EP_{nren} and EP_{tot}, fully describe the building energy performance.

The energetic expected annual losses, EAL_E, is calculated from the ratio of the cost of annual energy bills and the cost of reconstruction of a new building.

2.3 Case study buildings

The building analysed has been designed and constructed after the mid-1970s when first considerations about energy efficiency and seismic codes started to be discussed and established. It is a multi-storey cast-in-situ RC building with moment resisting frames and perimeter masonry (vertical hollowed bricks) infill walls.

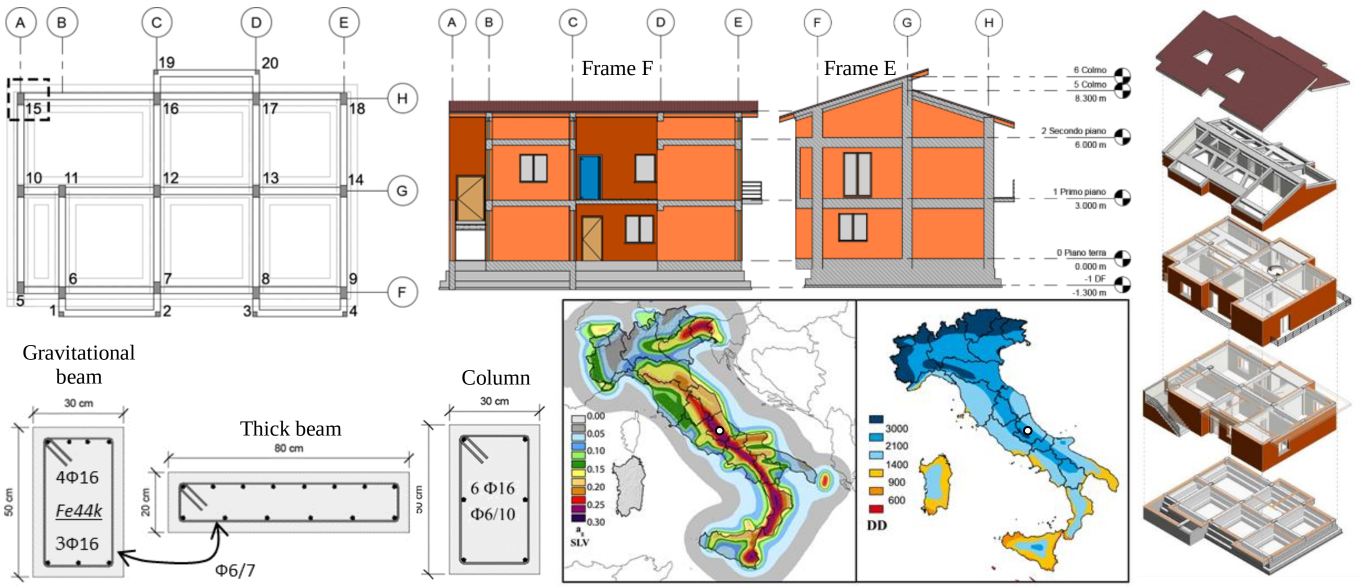


Figure 1. Characterization of the case study: foundation plan; frame section; exploded axonometry; main structural beam and column sections at the interface with the joint panel zone; geographical location (seismic hazard and climate demand).

A representation of the geometry, construction details and the geographic location of the case study building is given in Figure 1.

The design reflects a typical gravity loads-only design approach without specific attention to seismic actions and inadequate structural details such as: no capacity design (lack of proper strength hierarchy), excessive spacing of transversal reinforcement and lack of stirrups in the joint panel zone, fully analyzed (Del Vecchio et al. 2018). In terms of energetic assessment, the building is located in L'Aquila (climatic zone E), severe inadequacies affect the thermal performances of the building envelope consisting of double brick leaf with little insulation in-between, roofs without thermal break, double-glazed windows in hard wood and HVAC system made of old boiler powered by methane, with no cooling system, leading to a low consumption in the summer but at the same time a low comfort.

According to capacity spectrum method, Figure 2 (a) shows the comparison between the demand spectra, already scaled by the equivalent viscous damping (ξ) depending on the level of ductility reached the limit state of interest, for both the SLO and SLD an equivalent elastic viscous damping has been adopted, ξ=5%. The frames in Y-direction have a mixed mechanism close to the beam sway mechanism, while the frames in X-direction have a joint-mechanism, caused by the failure of all the external nodes. The infill walls cause an increased stiffness and strength but at the same time the limit states are reached for lower displacement compared to the bare frame. Figure 2 (b) show the calculation of (Seismic) Expected Annual Losses EAL_S. It can be noted that the building does not comply with current regulatory standards and expectation both in terms of safety index (IS-V=65% witch correspond to a $B_{IS\text{-}V}$ class) and the expected annual losses (EAL_S=1.85% witch correspond to a C_{PAM} class).

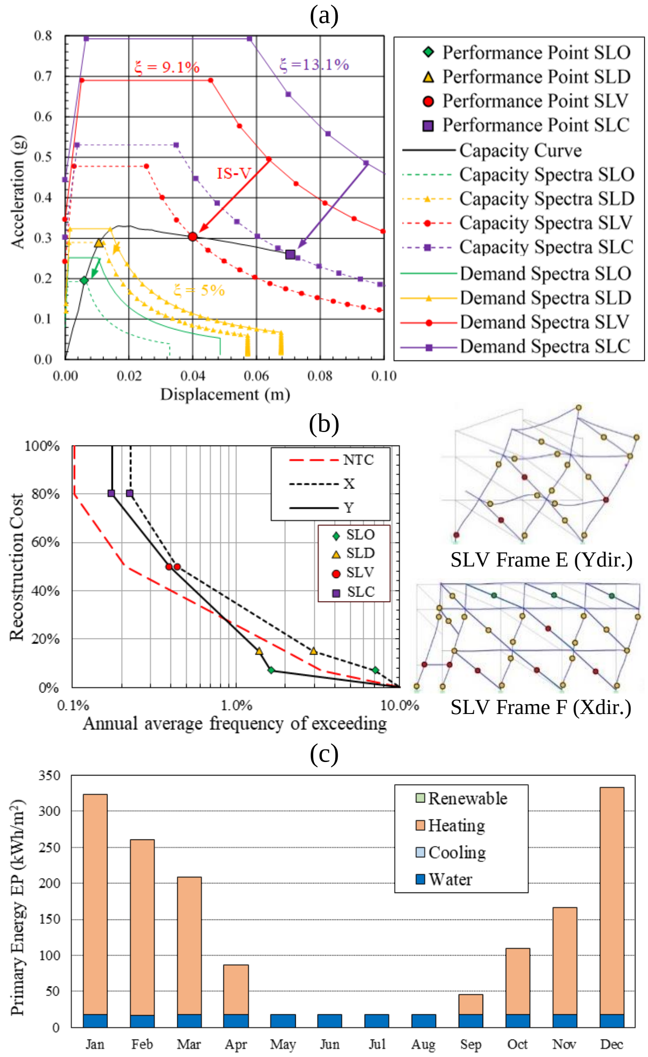


Figure 2. Seismic-Energetic Assessment of the Case study building: (a) Capacity vs. Demand within an Acceleration-Displacement-Response-Spectrum (ADRS); (b) (Seismic) Expected Annual Losses - EAL_S; (c) Global Energy consumption, EP_{gl}. and its contributions.

Figure 2 (c) shows the energy consumption of the building during the year, these are higher than the legal minimum of a quantity equal to 451% compared to the standard reference building.

As shown in Table 1, the building shows an inadequate behavior to the current seismic and energetic requirements, according with (Calvi et al. 2016) the building has a Green Resilience Index (GRI) of 10.76%, given by the sum of seismic and energetic Expected Annual Losses, this means that in less than 10 years energy consumption together with the risk of seismic collapse will equal the cost of reconstruction.

Table 1. Combined Seismic-Energetic Performance of the Case Study Building.

Index	NBS/RC	Class	Performance
IS-V	65%	B	Seismic
EAL_S	1.82%	C	
EP	451%	G	Energetic
EAL_E	9.02%	G	
GRI	10.84%	G	Combined

3 SEISMIC-ENERGETIC RETROFIT

3.1 Seismic Structural Retrofit

Seismic retrofit strategies can be typically divided into two macro categories: global and local interventions. Local intervention strategies are based on the localized updating of the strength, stiffness and/or ductility of specific structural elements to improve the overall global seismic response of the building. The hierarchy of strength can be analysed and restored at a beam-column-joint sub-assembly level, targeting, where possible the development of a flexural plastic hinges in the beam (i.e. weak beam-strong column mechanism).

The effects of various structural retrofit techniques applied on the case study buildings will be presented.

The reinforcement of columns and joint panel can be performed with Glass Fiber Reinforced Polymer (G-FRP) widely used as a seismic upgrade method; (Pampanin et al. 2007; Akguzel et al. 2012).

The Haunches Retrofit Solution (HRS) (Pampanin, Christopoulos et al. 2006; Genesio, 2012) is a local retrofit technique, based on the use of a diagonal metallic steel angles to change the static scheme and decrease the shear stresses in the joint. Both the FRP and Haunch retrofit intervention aim at inverting the hierarchy of strength and improving the sequence of local mechanisms (events). As a global intervention external unbonded post-tensioned rocking-dissipative systems can be used. These low-damage (PRESSS) technology has been widely developed in the past two decades for either frame and wall systems (Priestley et al. 1999; Rahman et al. 2000; Pampanin, 2005; Kurama et al. 2006), A "controlled rocking" mechanism at the critical interface activates two types of reinforcement: prestressed tendons providing re-centring and non-prestressed mild steel dissipation. Rocking systems are characterised by reduced/negligible residual deformations, minimal physical damage (due to a single gap opening/rotation concentrated at the critical interface), whilst having similar maximum displacements when compared to their equivalently reinforced monolithic counterparts. Controlling structural deformations in existing buildings with supplementary dissipation has been extensively studied, including dampers ranging from metallic (elasto-plastic), viscous, visco-elastic, friction etc (FEMA 365, 2000; fib, 2003). More advanced materials include Shape Memory Alloys having "memory" characteristics suitable for use in seismic applications (Dolce et al. 2000).

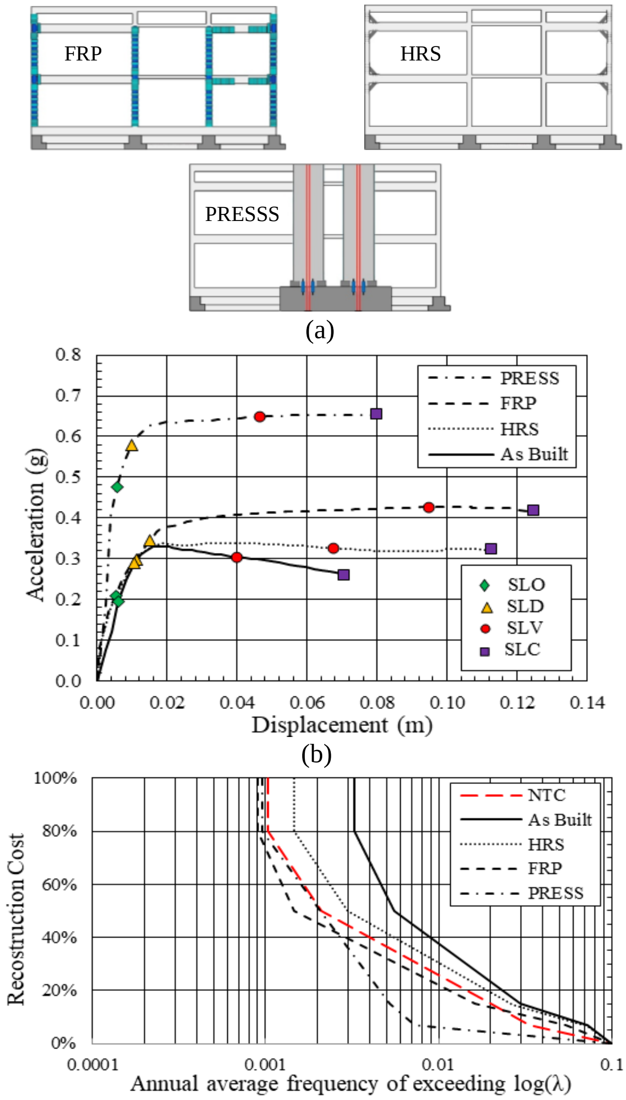


Figure 3. FRP, HRS and PRESSS Retrofit, (a) ADRS Push-Over capacity curve, (b) Expected Annual Losses.

The design of this three methods of intervention are shown in Figure 3: a local retrofit confinement of all the weak component (column, joint, and beam) with G-FRP; a local retrofit with a diagonal metallic haunch system HRS; a global drift/displacement control intervention consisting of four PRESSS external walls.

All these interventions are designed for a Life Safety Performance at a Design-Level Earthquake (SLV) and consequently they mainly increase the safety index IS-V, the limit to arrive in A_{IS-V} class is 80%; we want to clarify that for local interventions there is less control of the retrofitted performance, dictated only by the achievement of the beam sideway and possibly by the strengthening of the columns, while the global interventions can be calibrated by displacement base design to the required capacity, indeed it is obtained for the FRP 109%, for HRS 86%, instead for PRESSS 101% which is the lower limit of class A^{+}_{IS-V}.

The impact on the average expected Annual losses, EAL_S, is instead quite significantly different as they are influenced by the damage to the non-structural components; the As-Built building started with an EAL_S=1.82%, through low-damage wall the retrofitted building would have an EAL_S=0.62% that correspond to A^{+}_{PAM} class, the global retrofit intervention would thus lead to a reduction of 66% when compared to a limited/negligible reduction when adopting a local intervention with FRP (EAL_S=1.28%) or Haunches (EAL_S=1.52%) that reach a reduction of 30% and 16%, respectively.

3.2 *Energetic thermal plant retrofit*

Enhancing the energy efficiency of buildings implies the adoption of improvement measures on the building envelope and on the HVAC system, co-responsible for the internal climatic conditions.

The benefits of a more efficient HAVC system is analysed on the case study building: a pellet stove was added in the living rooms and the existing boiler replaced with a condensation one, increasing of EP of the building, the As-Built boiler consumes 75167 kWh/m^2 with no percentage of renewable sources while the condensing boiler could consume 44889 kWh/m^2 similar to consumption with the pellet stove in parallel 44901 kWh/m^2 but with a substantial contribution from renewable sources REN=16.7%; as shown in Figure 4 the replacement of the old boiler causes a decrease in consumption equal to 40.5% adding the pellet stove reaches a 50.2% decrease, (by deducting renewable source).

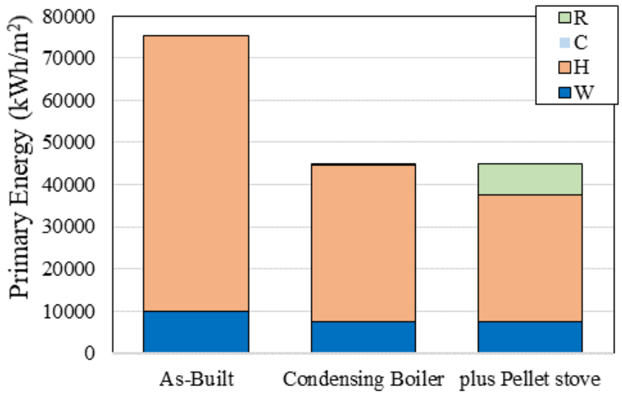


Figure 4. HAVC system Energetic Retrofit, Yearly Global Energy consumption, $EP_{,gl}$

The use of renewable sources is strongly supported by current legislation: energy consumed by renewable sources does not fall within the calculation of the Energy Performance, EP. Other examples of generators powered by renewable energy: installation of photovoltaic panels, geothermal heat pumps, solar panels for water preheating, or the use of "greener" energy vectors such as biomass; they are essential measures to obtain a passive-house. For simplicity, in the application presented in this paper the use of such alternative renewable energy sources has not been considered.

3.3 *Combined Retrofit of non-structural elements*

The building envelope can be seen as the "skin" of the building, since it acts as an interface between the interior and the external environment. Minimizing the heat transfer through the building envelope is undoubtedly the most direct method to reduce the need for heating and cooling (C2EF, 2012). There are a variety of insulation options, including "coat" solutions, forms of insulating concrete, spray foam, rigid foam and natural fiber insulation, these can be applied, in order of effectiveness: externally, in cavity walls or in in case the facade cannot be modified internally. Extensive state-of-the-art reviews on thermal insulation materials have been carried out by (Jelle, 2011; Schiavoni et al. 2016). While in the common opinion the main source of earthquake-induced damage is associated to the structural skeleton and components, past seismic events (Kocaeli 1999; L'Aquila 2009; Lorca 2011; Christchurch 2011) and studies have highlighted the importance of non-structural components in the evaluation of damage and losses from different perspectives: interaction with the structural behaviour, energy consumption and indoor comfort, economic/losses (Taghavi et al. 2003). To perform a combined seismic and energy efficiency rehabilitation, it is necessary to develop new economically sustainable and technically viable solutions based on combinations of materials and innovative systems, while keeping low overall costs and drastically reducing inactivity times (business interruption or downtime). An interpretation comes from (Marini et al. 2017) that suggested the opportunity to enhance resiliency and seismic safety of existing under-designed building through the introduction of a life cycle thinking framework consisting of a double skin with the multiple function of structural retrofit and energy refurbishment.

According to a performance-based design, the insulation material should be adequately protected from seismic actions, so it would be necessary to impose a low- or limited damage to the Seismic Service Limit State (in Italy correspond to design earthquakes for the operating limit state SLO and damage limit state SLD) of the new housing components.

To preserve these elements, we can distinguish between Strength and Deformation/Ductility retrofit strategies. An overview of solution to reduce the damage to non-structural facades and infills have been given by (Baird et al. 2014; Baird et al. 2012; Tasligediket al. 2011; Tasligedik et al. 2014).

The Strength interventions strategies modify the failure mechanism by adding new layers capable of providing tensile strength. A well-executed intervention therefore allows to move from a sliding or a diagonal tension cracking mechanism to a (stronger) diagonal compression/ crushing mechanism. Options available in terms of reinforcing materials are: Reinforced Concrete Masonry (RM) (Sugano, 1996), Textile Reinforced Mortar (TRM) (Papathanasiou et al. 2007). These technologies modify the infill panels behaviour from non-structural component into structural seismic-resistant elements.

The Deformation/Ductility intervention strategies consist on the disconnection of the infill wall to minimize interaction with the frame and damage. Depending on the position of the disconnection joint to the filling material it can be distinguished in : horizontal Sliding Joint (Cardone et al. 2017); low damage unreinforced clay brick infill wall (LDiw) (Tasligedik et al. 2014). Another more invasive option consist in replacing or introducing a larger disconnection on the existing infill walls and installing cladding panels connected to the frame with slotted or dissipative connections (Baird et al. 2011), where the damage occurs for higher drifts.

Figure 5 show a summary of the different mechanism and the force-drift/rotation behaviour of these retrofit strategies for infill walls.

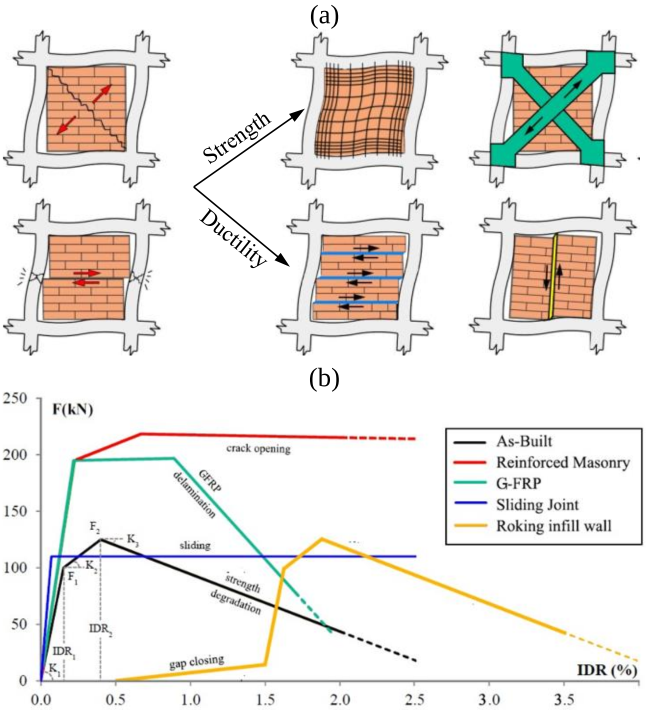


Figure 5. (a) Strength and Ductility seismic retrofit strategies on infill-wall; (b) equivalent strut capacity of infill walls in the as-built or retrofitted configuration

Starting from considerations on sustainability and dual efficacy, as show Figure 6 four categories of combined interventions on external infill wall have been selected: (a) glued and anchored thermal insulation material combined with Textile Reinforced Mortar TRM or RM; (b) cavity thermal insulation combined with out-of-plane retaining devices and LDiw; (c) cladding systems that can be combined with any type of structural seismic intervention, they simplify the labour on the components thanks to the demolition and substitution; (d) internal wall heating or phase change materials (PCM) combined with seismic resistance strategies (Bournas, 2018).

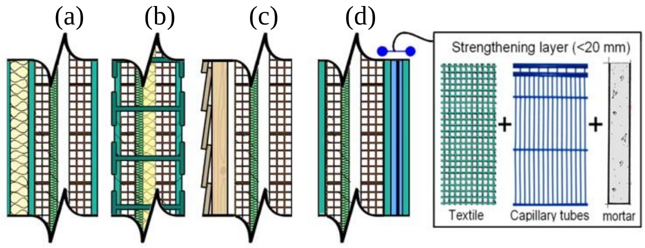
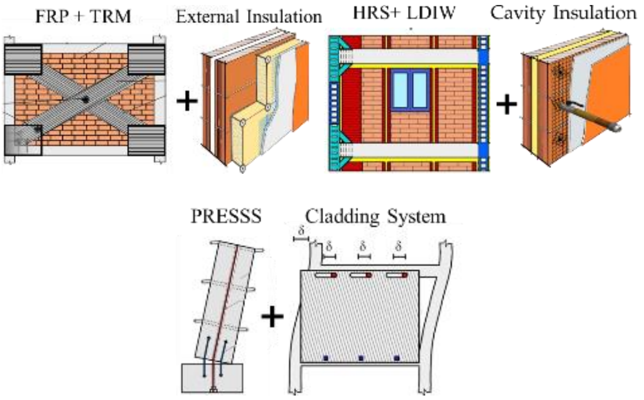
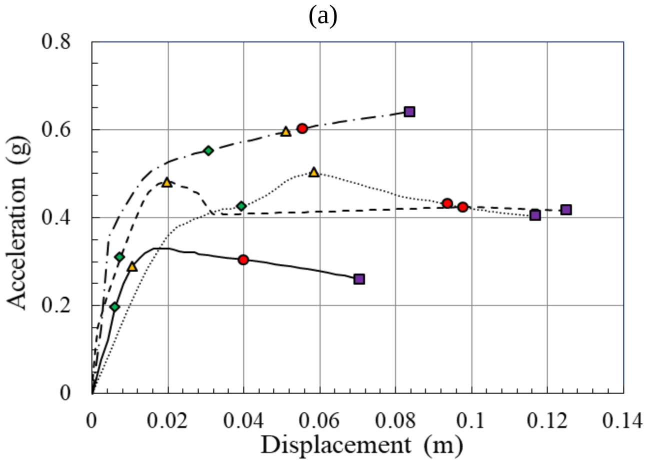


Figure 6. Construction details to combine energy efficiency and minimize damage to infill walls

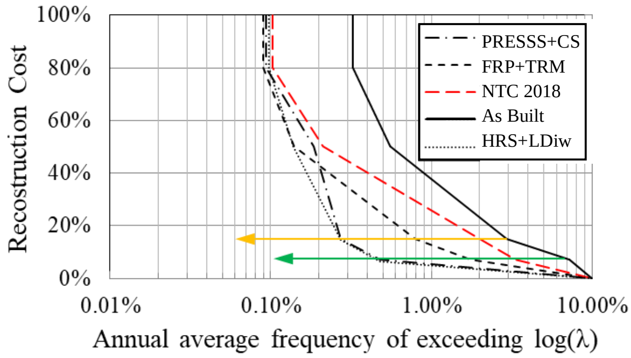
Three insulation methods have been analysed: cavity insulation with polyurethane foam (filling the 60 mm cavity), bonded external insulation in expanded polystyrene panel (80mm) and wood cladding panel with cork panel. All three interventions also include the replacement of windows and roof insulation. The results are presented in terms of on energy consumption and energy class. The three abovementioned retrofit structural retrofit and HAVAC intervention have been combined with compatible non-structural retrofit intervention to enhance the thermal upgrading of the envelope while at the same time protecting the investment from the earthquake actions.



(a)



(b)



(c)

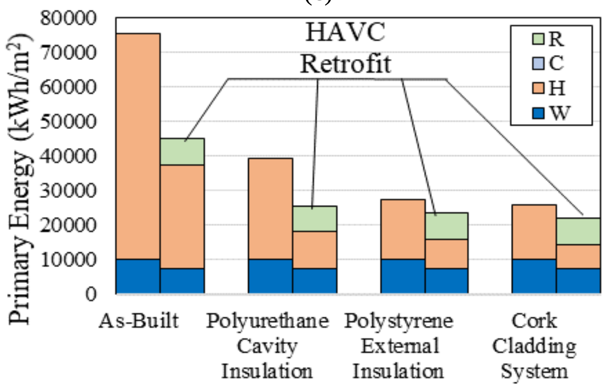


Figure 7. Combined Retrofit options: (a) ADRS Capacity vs. Demand; (b) EAL_S; (c) EP_{gl}.

To protect the external insulation FRP have been merged with TRM; HRS has been combined with cavity insulation and Low Damage infill wall by preparing more vertical gaps; external unbonded post-tensioned rocking-dissipative (PRESSS technology) walls have been associated with Cladding System, in this case the owners will be free to maintain the tiling by introducing disconnections to limit the level of structural-non-structural interaction or totally dismantling them.

The results show that implementing separately seismic and energy efficiency interventions does not lead to a satisfactory performance.

Performing only structural retrofit it is not always possible to seismically align the building to the NTC 2018 standards, indeed to obtain satisfactory results of the EAL_S in local interventions it is necessary to protect the infill walls to improve the seismic behaviour at the SLO and SLD; deformation/ductility non-structural retrofit, rather than strength, enhancement in general give greater performance advantages as show Figure 7 (a) (b); interventions on the heating system only allow a maximum of one class E to be reached, improving the thermal performance of the envelope while maintaining an obsolete heating system is not recommended but certainly more effective than replacing the system without insulating the envelope as show Figure 7 (c).

The retrofit with FRP on structural components is very effective, while if applied to the non-structural elements give limited benefits, yet it is in any case an excellent method of protection for the external insulating material reaching EAL_S=0.73%; combining with the "insulation" insulation and the complete HAVAC intervention, EAL_E = 1.91% is reached, which corresponds to an $A1_{EP}$ class.

The Haunches (HRS), which alone did not allow to reach 100% of IS-V, if coupled with LDiw give excellent results, both in terms of security (IS-V = 120%) and in terms of expected annual losses with a A^{+}_{PAM} class and EAL_S=0.498%; by intervening on the heating system and isolating the infill in cavities, an EAL_E=2.17% is reached which corresponds to a B_{EP} class.

The solution with PRESSS walls combined with new cladding system appears to be the best e combination of technologies with the greatest benefits: EAL_S=0.49% with a A^{+}_{PAM} class and EAL_E=1.74% with a $A1_{EP}$ class; yet it remains to investigate the feasibility.

A summary of the results is given in Table 2, the last step is the evaluation of the costs of the interventions so as to implement a cost-benefit analysis to choose the best combination of technological options; further developments will be dealt with in subsequent studies.

Table2. Combined retrofit results

HAVC Retrofit			Infill-wall Retrofit		Structural Retrofit			
+ Pellet Stove	Condensing Boiler	As Built	EAL (%)		As Built	FRP	HRS	PRESS
4.49	5.37	9.02	As Built	As Built	1.82	1.28	1.52	0.62
E	F	G			C	B	C	A
2.17	3.28	4.7	Cavity thermal insulation	Low damage infill wall	0.55		0.498	
B	D	E			A		A+	
1.91	3.08	3.3	External thermal insulation	Texile Reinforced Mortar	0.85	0.73		
A1	D	D			A	A		
1.74	2.89	3.09	Wood Cladding Panel	Removal			0.53	0.49
A1	C	D					A	A+

4 CONCLUSION

Greater attention has been raised in the last decade around environmental sustainability aspects, particularly in the construction sector, being one of the main contributors of all aspects of sustainability: it is one of largest economy generator and employer, it consumes a third of the primary energy and produce Greenhouse Gases (GHG) in same proportions. It also represent one of the main factor (vulnerability) in terms of seismic risk both in terms of life safety and economical losses.

This study presented a decision-making support approach, based on the combination of seismic and energy efficiency upgrading through a practical example of a simulated rehabilitation intervention on a residential case study building, designed before the introduction of seismic and environmental-energy efficiency codes.

Traditional and innovative retrofit strategies have been considered and adequately combined, confirming the feasibility and efficiency of such a multi-factor/performance approach.

Seismic safety should be the main decision-making criteria to guide a retrofit interventions. Nevertheless local interventions are not always sufficient to adequately reduce the seismic risk, as they do not reduce the drift demand at the low-level earthquake intensity and thus do not protect the infill wall and non-structural elements that mostly affect the economic losses, EAL_S..

Thermal insulation, ventilation, greening or the introduction of energy generation systems are effective measures to reduce energy consumption and CO_2 emissions; therefore a collaboration between the various professional figures is critically needed .

The building envelope system – typically considered as composed of non-structural elements - incorporate the main seismic and thermal weaknesses of residential RC buildings. For such reason they should be the components to focus on for a combined rehabilitation/retrofit intervention aiming at maximizing seismic and energy performance. Retrofit strategies on the non-structural elements based on deformation/ductility - rather than strength - enhancement in general give greater performance advantages, if properly combined with structural solution interventions. It is important, on a case-by-case basis to investigate whether they are also equally advantageous economically. As part of future developments, many other solutions, materials and combinations should be investigated. Although the behaviour of internal partitions, ceilings, services and contents have not been explicitly considered in this study for simplicity, in future studies - partly under-going - an holistic investigation of the behaviour of the building system as a whole is required.

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