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Combined seismic and energy upgrading of existing reinforced concrete buildings using TRM jacketing and thermal insulation

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Abstract. The concept of the combined seismic and energy retrofitting of existing reinforced concrete (RC) buildings was examined in this paper through a number of case studies conducted on model buildings (simulating buildings of the '60s-'80s in southern Europe) constructed according to outdated design standards. Specifically, seismic and thermal analyses have been conducted prior to and after the application of selected retrofitting schemes, in order to quantify the positive effect that retrofitting could provide to RC buildings both in terms of their structural and energy performance. Advanced materials, namely the textile reinforced mortars (TRM), were used for providing seismic retrofitting by means of jacketing of masonry infills in RC frames. Moreover, following the application of the TRM jackets, thermal insulation materials were simultaneously provided to the RC building envelope, exploiting the fresh mortar used to bind the TRM jackets. In addition to the externally applied insulation material, all the fenestration elements (windows and doors) were replaced with new high energy efficiency ones. Afterwards, an economic measure, namely the expected annual loss (EAL) was used to evaluate the efficiency of each retrofitting method, but also to assess whether the combined seismic and energy retrofitting is economically feasible. From the results of this preliminary study, it was concluded that the selected seismic retrofitting technique can indeed enhance significantly the structural behaviour of an existing RC building and lower its EAL related to earthquake risks. Finally, it was found that the combined seismic and energy upgrading is economically more efficient than a sole energy or seismic retrofitting scenario for seismic areas of south Europe.

Keywords: advanced materials; building envelope; energy retrofitting; infill strengthening; textile reinforced mortar (TRM); thermal insulation

1. Introduction

The vast majority of European building stock comprises residential buildings, with a percentage of approximately 75%. From these, around 40% were built before the 1960s, 45% during the period 1961-1990 and only 15% after 1991, with the respective percentages for the seismically active regions of south Europe being 37%, 49% and 14% (Atanasiou *et al.* 2011). Since most of these existing buildings do not conform to the modern seismic codes (e.g., Eurocodes) or energy standards (e.g., Energy Performance of Buildings Directive), they are prone to excessive damage, when subjected to earthquakes, and are also energy deficient. This could result in high economic losses due to damage to the existing infrastructure and even human casualties in the seismic-prone countries of south Europe. There is therefore an urgent socio-economic need to upgrade the existing building stock for decreasing their associated risks.

1.1 Deficiencies in existing buildings

When it comes to the seismic performance of existing reinforced concrete (RC) buildings, there are many common deficiencies compromising their structural integrity. Design standards before the '80s were considering seismic actions less than 50% compared to modern ones (e.g., Eurocode 8 2004); reinforcement detailing measures were poor, and structural analyses were conducted using over-simplified and approximate models. As a result, in existing RC buildings it is common to observe lightly reinforced, small column sections, inadequately anchored longitudinal and transverse reinforcement, as well as lack of any kind of capacity design. Other deficiencies, attributed to the poor practices employed during the construction phase, include the formation of short columns because of the poorly designed infill walls, soft-storey mechanisms, as well as the negative effect of inappropriately positioned-and connected to the frame-stairways. All these deficiencies have, in the past, resulted in excessive damage to old RC buildings due to earthquakes. It is important to note that many of these deficiencies are directly related to the masonry infills, which for many years were regarded as non-structural elements with no significant contribution and were not

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considered at all during the design phase. Such a conception holds approximately true for modern structures with strong frames and shear walls but lies far from reality when it comes to old RC structures, consisting of frames with low lateral stiffness and resistance, as is almost always the case.

A number of deficiencies can also be observed if one examines an existing structure from its energy efficiency point of view. The first regulations date back to the late 1950s and the early 1960s in Scandinavian countries. Later, more countries followed after the oil supply crisis in the 1970s, but the actual implementation of energy-related regulations in construction was in most cases delayed. In Greece, for instance, according to the Greek Statistics Agency (ELSTAT), 45.6% of the residencies do not have any kind of thermal insulation at all (Daskalaki *et al.* 2016). Therefore, the lack of insulation, the energy deficient fenestration surfaces used, but also the old and inefficient mechanical equipment used for heating, cooling and domestic hot water needs, result in high energy consumptions, hence high economic losses and increased CO_2 emissions.

1.2 Retrofitting solutions

The above-mentioned problems have been addressed many times in the past by the research community and numerous studies have been conducted in the field, targeting the development of methods to overcome them.

As far as seismic retrofitting of RC structures is concerned, a plethora of different techniques have been proposed over the last decades. Structural upgrading can be achieved either through the repair (if needed) and upgrading of individual load bearing elements (beam, columns, joints etc.) or through the addition of an entirely new lateral load resisting system. In the former category fall various techniques like using simple RC jackets to rehabilitate all types structural elements (Júlio *et al*. 2003), FRP jackets to upgrade beam-column regions (e.g., Antonopoulos and Triantafillou 2003, Tsonos 2008), self-compacting concrete (Chalioris *et al*. 2013, Chalioris *et al*. 2014) or epoxy resins (Kalogeropoulos 2016) to repair existing elements, high-performance fiber-reinforced concrete in combination with FRP jackets to enhance the behaviour of beam-column joints (Tsonos 2014) etc. More recently the textile reinforced mortar (TRM) jacketing technique was proposed, addressing problems of FRP at high temperatures (i.e., Tetta and Bournas 2016, Raoof and Bournas 2017a, b). TRM jacketing is highly effective in seismic retrofitting of RC structures (Bournas *et al*. 2009, Koutas *et al*. 2019).

In the category of new lateral load resisting systems, possible solutions are the addition of external steel bracing, the infilling of a frame bay with RC (Poljanšek *et al*. 2014), the upgrading of selected masonry infills with TRM to transform them into reliable lateral-load resisting elements (Koutas *et al*. 2015a, 2015b, Koutas and Bournas 2019) etc. The present paper utilizes the last-mentioned method, namely the TRM infill strengthening, in the case studies that follow.

Energy upgrading can be realized by acting either on the structure's external envelope or on its mechanical equipment. The former can be achieved simply by adding insulation materials on the façades of the building at hand and/or by substituting the fenestration surfaces with newer ones, more energy efficient (double-pane windows, balcony doors etc.), so as to minimize the heat losses through the building's skin. The latter can be realized through the replacement of the structure's mechanical equipment providing the energy needs with newer and more efficient solutions, like heat pumps, solar panels etc. Combining these two schemes of energy upgrading, it is feasible to make an old building behave like a new one in terms of energy efficiency.

In the context of this work, the selected seismic retrofitting scheme was the strengthening of the external masonry-infilled RC frames with TRM (Koutas *et al.* 2015a, 2015b), due to its simplicity and high effectiveness. Energy upgrading is assumed to be achieved by the overall enhancement of the thermal shell (added thermal insulation externally and fenestration replacement), without acting at all on the buildings' mechanical equipment.

It is noted that the amount of the seismic reinforcement and the insulation were chosen arbitrarily by the authors and not in order to satisfy a specific standard, since this work is presented as a proof of concept. Therefore, no verifications were carried out to check whether the reinforcement/insulation amount is sufficient or not. Of course, when applied in engineering practice, the amounts of TRM and insulation thickness have to be chosen so that the corresponding standards are satisfied. For example, seismic verifications should be made according to Eurocode 8 Part 3 or FEMA-306.

1.3 The integrated approach

Up until recently, seismic and energy retrofitting have been thought of as two different and uncoupled upgrading schemes that one could apply to a building at different times, therefore the interconnection between them has always been omitted (Calvi *et al.* 2016, Marini *et al.* 2017). This dependence, however, does exist, as a potentially high seismic risk can affect the environmental impact of an existing building (Belleri and Marini 2016). Simply put, a building receiving only energy upgrading will always be prone to structural damage if it is located in an area of high seismicity. In that case, if an earthquake was to occur, the structure would undergo damage that, depending on the intensity, could even lead to collapse and loss of human lives. But even earthquakes of low to moderate intensity would quite possibly damage the thermal insulation material applied to the building's envelope, jeopardizing the funds invested for its energy retrofitting. On the other, less common case, a building that has been retrofitted only seismically, will be future-proof in terms of structural performance, but will continue consuming large amounts of energy needed to overcome the inherent heat losses due to its old construction practices.

A way to overcome all the above-mentioned problems, is to stop thinking of the two types of upgrading as separate, but instead as tightly connected to each other. This means that both of them should be applied at the same time, leading to buildings that are both seismic and energy proof. Naturally, such an integrated approach will require a higher

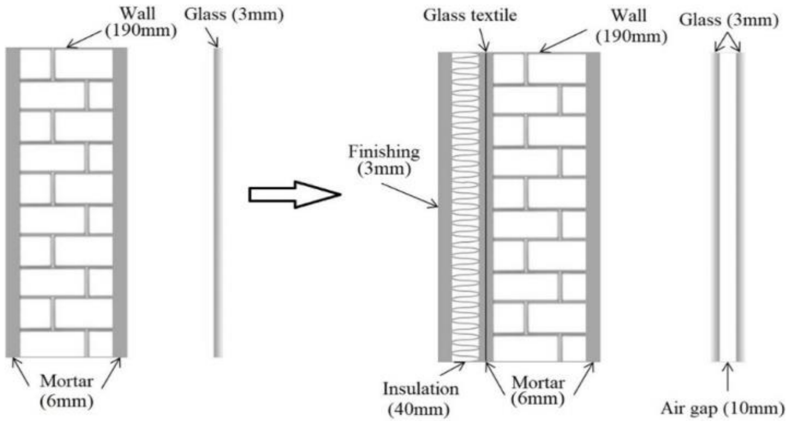
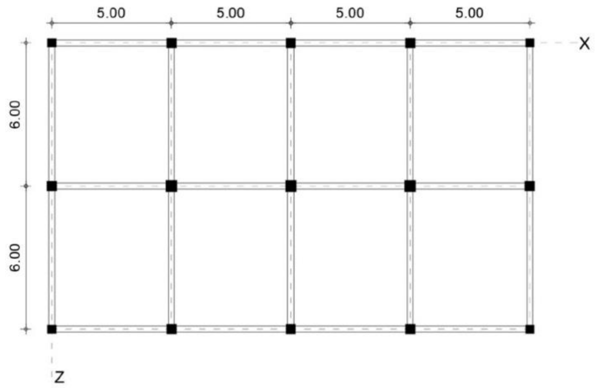
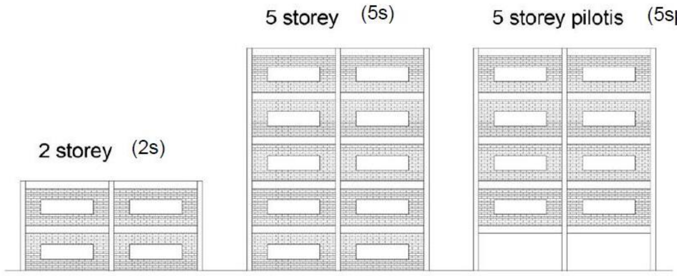


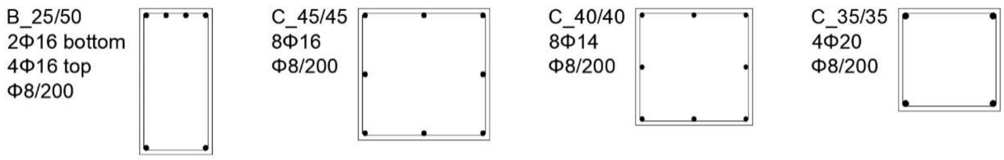
Fig. 1 TRM and Insulation schematic configuration for the walls and the fenestration surfaces



(a) Plan view of the building models



(b) Front view of the building models



(c) Steel detailing of concrete members

Fig. 2 Building configurations used in case studies

initial financial investment, which might not be economically affordable. However, if one takes into account the lower construction costs (in comparison to those if the same upgrades were to be applied separately), due to reduced labour and scaffolding costs, the combined retrofitting is a reasonable choice to follow, as it is demonstrated in this investigation.

The concept of the combined seismic and energy retrofitting with advanced materials was proposed for the first time and investigated experimentally for the case of masonry subjected to out-of-plane or in-plane loading in Triantafillou *et al.* (2017), Triantafillou *et al.* (2018) and Karlos and Triantafillou (2018). These studies introduced for the first time the combination of TRM with standard or even highly fire-resistant thermal insulation materials. A similar system for the concurrent seismic and energy retrofitting for the case of RC buildings was proposed in Bournas (2018a), Bournas (2018b), Mastroberti *et al.* (2018). The same concept, namely that of combining TRM jacketing with thermal insulation material is further explored in this paper via a series of case studies on RC buildings. Fig. 1 illustrates schematically an infill wall (left) and a fenestration section (right) before and after their retrofitting following the integrated approach, as it was assumed in the case studies of the present paper.

2. Methodology

For the purposes of this study it was necessary to carry out a large number of both seismic and energy simulations. To achieve this, two open-source software packages were used, namely OpenSees (OpenSees 1999) for the earthquake simulations and EnergyPlusTM (EnergyPlus 1997) for the energy ones. The next sections describe in detail the modelling approach in both cases.

2.1 Structural configurations

The structure that was analysed is a regular in plan RC building (see Fig. 2(a)) with four bays, 5 m wide in the *X*-direction, and two bays, 6 m wide in the *Z*-direction, yielding a total floor area of 240 m^2, that could accommodate two to three apartments. The three different structural configurations (2-storey, 5-storey with infills and 5-storey with pilotis) are illustrated in Fig. 2(b).

As a case study, the three building configurations were detailed according to the prior to 1985 Greek seismic provisions, which accounted for a lateral load of 6% of the building weight. The concrete class was assumed to be C16/20 and the steel quality S400. Practically, this design was done twice, once for the 2-storey and once more for the 5-storey structure, as the infill-frame interaction was omitted during this phase, according to standard practice. The above procedure yielded the steel detailing arrangements listed below and given in Fig. 2(c).

- The beams in all cases are 250x500 mm with 4Φ16 at the top and 2Φ16 at the bottom flange at the supports (B_25/50).
- All the columns (15 in total) of the 2-storey building are 350×350 mm with 4Φ20 (C_35/35).
- The central columns (3) of the 5-storey buildings are 450×400 mm with 8Φ16 (C_45/45).
- The side columns (8) of the 5-storey buildings are 400×400 mm with 8Φ14 (C_40/40).
- The corner columns (4) of the 5-storey buildings are 350×350 mm with 4Φ20 (C_35/35).
- Shear reinforcement was Φ8/200 for all the elements in all three cases.

Apart from the concrete members, the infills of the perimeter are assumed to be made up of 9-hole bricks (9×9×19 cm) forming a double brick lining wall of a total thickness of 19 cm. The compressive strength of the walls perpendicular to the bed joints was taken equal to 5.1 MPa, the shear cracking stress was 0.39 MPa, the masonry shear modulus was 1.38 GPa and the masonry elasticity modulus was 3.37 GPa. All these infills are also assumed to have a central opening which occupies 25% of their total clear area to account for the existence of the fenestration surfaces. These are the members that are reinforced through the TRM strengthening scheme using a polymer-coated *E*-glass textile with a 25×25 mm mesh and weight of 405 g/m^2. This textile has a tensile strength equal to 115 kN/m, an ultimate tensile strain of 2.5% and an elasticity modulus equal to 73 GPa. The presence of the textile on the masonry infill serves a dual purpose: it enhances the masonry's shear cracking stress and shear modulus (the other properties are minorly affected) making it stiffer and reducing the possibility of cracking while also adding an extra diagonal macro-element inside the frame able to withstand substantial tensile forces (see section 2.2.1).

For the retrofitted buildings, the TRM strengthening technique was assumed to be applied as is described below. In all cases, only those infills located at the perimeter of the buildings are retrofitted with 1 or 2 layers of the above-mentioned textile embedded in a cementitious mortar which is applied on the faces of the infill, either externally and internally (two-sided TRM) or only externally (one-sided TRM).

- 2-storey building: infills of both floors are reinforced with two layers of two-sided TRM.
- 5-storey building: infills of the first two floors are reinforced with two layers of two-sided TRM, the 3rd and 4th floor with one layer of one-sided TRM and the last floor with one layer of one sided TRM.
- 5-storey building with pilotis: One of the two bays in the *Z*-direction and two of the four in the *X*-direction are masonry infilled first with infills identical to those of the above floors (without openings) and then reinforced with one layer of two-sided TRM. Walls of the 2nd floor are reinforced with two layers of tow-sided TRM, of the 3rd with one layer of tow-sided TRM, of the 4th with one layer of one-sided TRM and of the 5th floor are not reinforced at all.

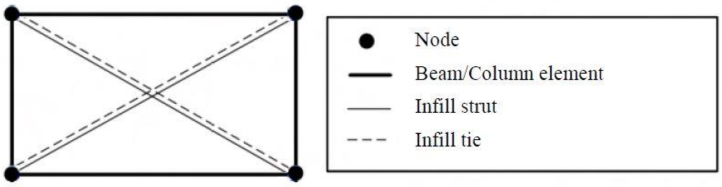
2.2 Seismic modelling

In order to quantify the seismic performance of the model buildings, non-linear dynamic analyses were performed using a total of 11 real earthquake records, mainly from the Greek territory but also from Italy, Turkey as well as some well-known from the rest of the world. Specifically, the earthquake records used were El Centro (1940), Friuli (1976), Kalamata (1986), Loma Prieta (1989), Roma (1990), Aegion (1995), Kobe (1995), Athens (1999), Sakaria (1999), Kefalonia (2014) and Lefkada (2015).

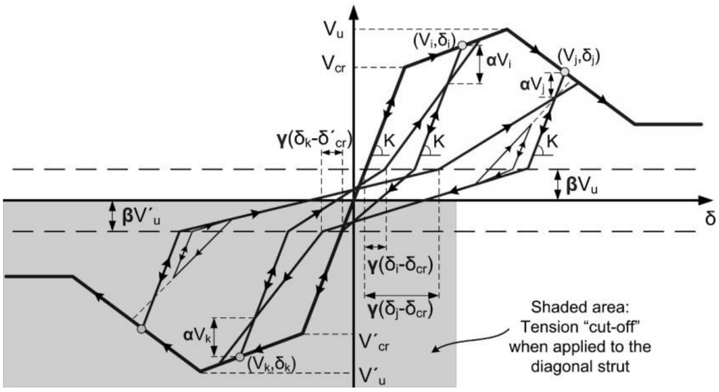
Both the geometric and the material non-linearities were taken into account through OpenSees. Because of the large number of analyses, as well as the abundance of the results, the accelerograms were inserted only in the weak *Z*-direction (Fig. 2(a)), which was the most prone to damage due to the smaller number of bays. However, as an approximation, for the evaluation of economic loss and the design of the retrofitting schemes, it was assumed that the damage and the relevant retrofitting would be evenly distributed to both directions in the case of an actual earthquake, during which accelerations are imposed in both directions.

2.2.1 Numerical modelling and materials

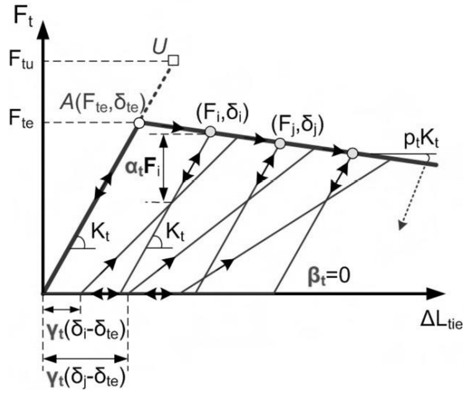
Linear finite elements were used for modeling the RC buildings. All RC members were simulated using distributed plasticity elements. Each column or beam was modeled with an element of type *forceBeamColumn* with 5



(a) Finite element model configuration



(b) Hysteretic behavior of wall infill strut (Fardis and Panagiotakos 1997)



(c) Hysteretic behavior of wall infill tie (Koutas *et al*. 2015b)

Fig. 3 Masonry infill simulation and hysteretic behavior

Table 1 Infill properties used for seismic simulations

Case	Members representing masonry			Members representing TRM	
	K (kN/m)	V_{cr} (kN)	V_u (kN)	K (kN/m)	$V_{\max}$ (kN)
Initial	226834	160.3	452.8	-	-
2layers-2sides	435587	349.3	504.5	8410	87.1
1layer-2sides	312307	246.6	478.5	4451	65.2
1layer-1side	269571	203.4	465.7	2225	32.6

Remarks:

- The above properties refer to the shear capacity/stiffness of the walls. To get the corresponding values for the diagonal elements, the above have to be rotated accordingly.
- For the masonry members, the parameters α, β, γ, p_1 and V_{res} of the Fardis and Panagiotakos (1997) model were taken as 0.15, 0.2, 0.2, 0.015 and $0.5V_u$ respectively according to Koutas *et al.* (2015b).

integration points along its length. For each integration point, a previously defined (with an MS Excel-based program) moment-curvature relationship was attached, using the *ModIMKPeakOriented* material provided by OpenSees. It is noted that phenomena such as bar slippage cannot be captured inherently with distributed plasticity models. Moreover, since the integration points were described by pre-specified moment-curvature relationships, the biaxial bending and axial force interaction was not considered. However, the level of approximation achieved with the proposed scheme was more than adequate for the purposes of this work, given the fact that the structural behaviour of the structure is heavily controlled by the infill walls, whose simulation entails many more uncertainties. The axial, torsional and shear behavior were assumed to be linear elastic.

Masonry infills were modeled by using the standard strut-and-tie method. Such a model is simple to use but has the disadvantage that it can only provide the global behavior of RC frames, without capturing localized phenomena. Each masonry infill bay was represented by two or four diagonal truss-like elements connected to the beam-column joints, depending on whether the infill was retrofitted or not (the retrofitting was represented by two extra elements, see Fig. 3(a)). For those elements modeling the masonry infill, the axial behaviour proposed in Fardis and Panagiotakos (1997) was adopted. On the other hand, the elements representing the TRM reinforcement were modeled using the axial behaviour proposed in (Koutas *et al.* 2015b). The hysteretic behaviour and the backbone curves assumed for the infill models are illustrated in Figs. 3(b)-3(c) and the properties used in the analyses are summarized in Table 1. In OpenSees, the desired behaviour was achieved by using the *twoNodeLink* element along with the Pinching4 material to get the desired axial behaviour, after configuring the parameters of the latter.

Modelling an infill wall is a procedure that involves a large number of uncertainties, especially if openings exist in its body, as is almost always the case. When detailed finite element models are used, the exact geometry is idealized realistically through the proper mesh generation. However, in the more common case, where strut macro-models are used, capturing the actual behavior can be much more challenging. To overcome this problem, typically reduction factors for the strength and stiffness of the infill are assigned. These are based on empirical equations, which, given the dimensions of the opening in relation to the infill, provide a reduction factor, ρ. Moreover, in almost all cases, the assumption is that the opening is located in the middle of the masonry infill. The five most commonly used formulas found in the international literature for the calculation of ρ are plotted in Fig. 4, which shows the high dispersion inherent in the problem. A recent model for ρ

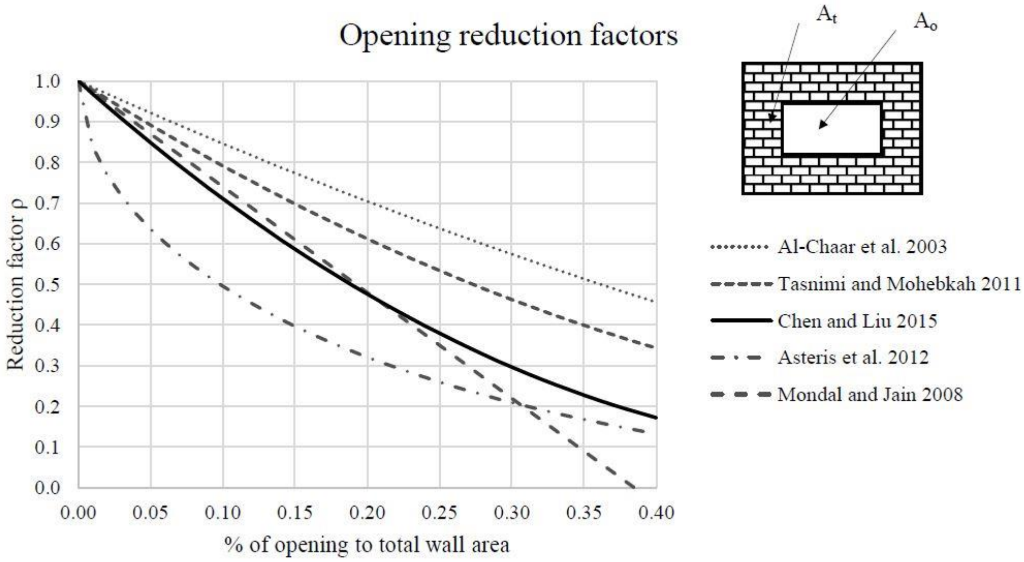
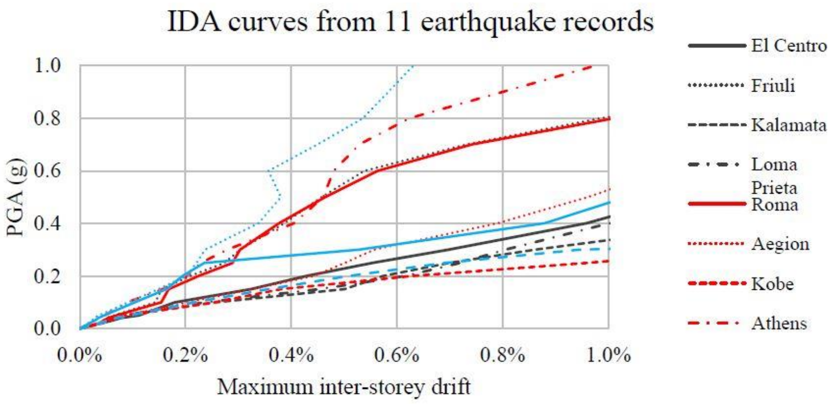
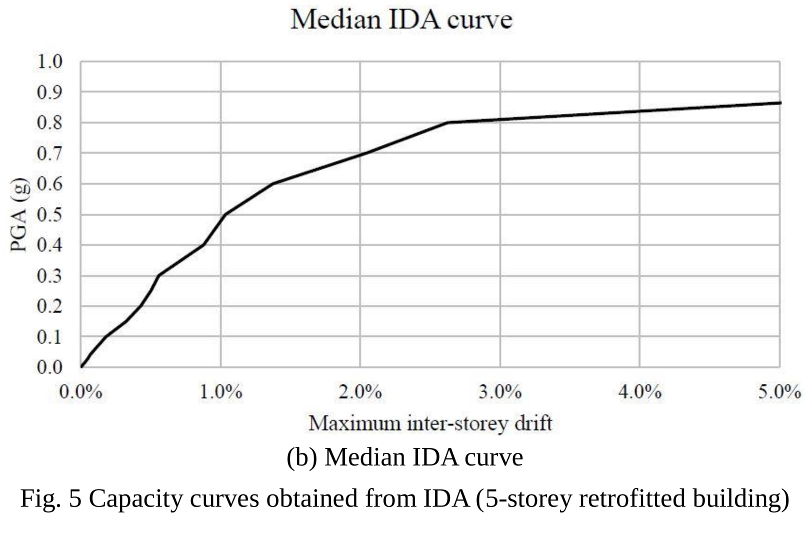


Fig. 4 Infill opening reduction factors



(a) IDA curves from 11 earthquake records (5-storey retrofitted building)



(b) Median IDA curve

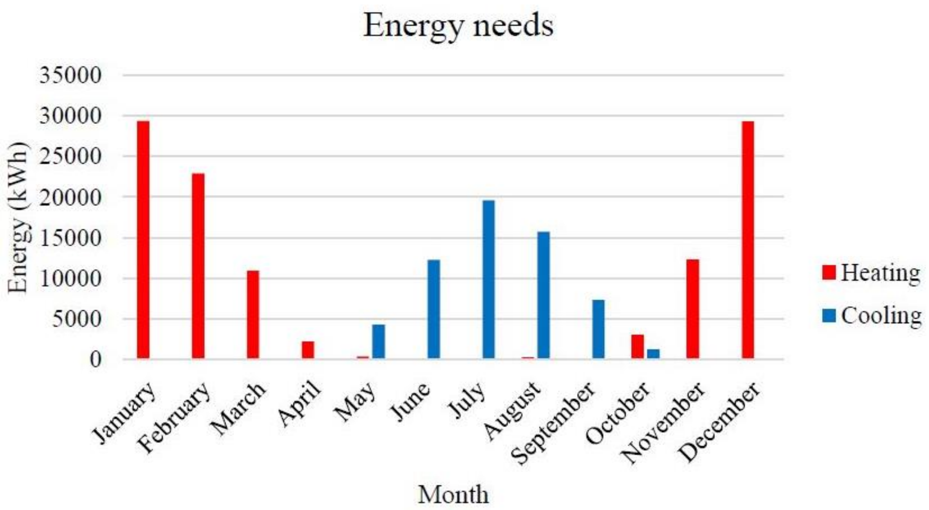
Fig. 5 Capacity curves obtained from IDA (5-storey retrofitted building)

(black continuous line in Fig. 4), which was also adopted in this study, was proposed in Chen and Liu (2015) and is given by Eq. (1).

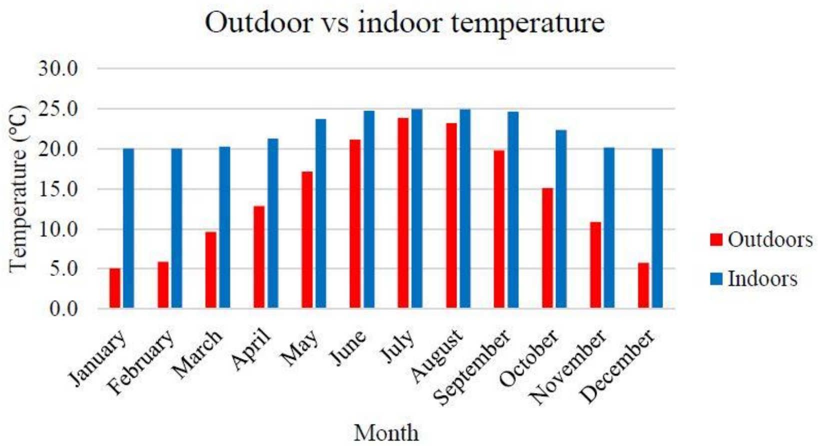
$$\rho = 1 + 2.751a_a^2 - 3.17a_a \tag{1}$$

In Eq. (1) a_a is the ratio of the opening area to the total clear area of the masonry infill. This model was chosen on the grounds that its curve lies close to the median curve of the five shown in Fig. 4. Since this work is presented as a proof of concept, no sensitivity analysis was carried out, however for a more detailed examination of the problem such a procedure would be advisable.

In any case, it is important to note that the presence of masonry infills even when they have openings is in most



(a) Heating and cooling needs during a year



(b) Indoor and outdoor temperature variation during a year

Fig. 6 EnergyPlusTM analysis output, 5-storey building in Florence

cases beneficial for RC buildings (Kakaletsis and Karayannis 2008). Specifically, they increase the lateral resistance and stiffness and also provide additional ductility and energy dissipation reserves, especially when constructed with strong masonry units. When openings are present, then cracking and separation from the surrounding frame takes place earlier and energy absorption stops in higher drifts. Lastly, if designed so that they do not form squat columns and their shear resistance is less than that of the frame columns, then brittle collapse mechanisms can also be avoided.

2.2.2 Earthquake analyses

Each building configuration was analyzed through Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell 2001). This method comprises a large number of non-linear time-history analyses, applied for various earthquake records, by scaling them from very small (0.001g) to very large (1.0 g) Peak Ground Accelerations (PGA) – 17 in total. This resulted in 1122 analyses, which were conducted for the initial and the retrofitted configurations and the 11 selected accelerograms. The damage parameter selected for all cases was the maximum inter-storey drift (IDR), which is the most typical damage parameter; in almost all cases, both retrofitted and not, this drift was recorded in the first floor. This choice was made on the ground that inter-storey drifts can be extracted easily from the OpenSees analyses, something that was very important, given the large number of analyses that had to be run. Furthermore, if a more elaborate way of representing the damage were to be used, that would be done by using the well-known chord rotation angles for the concrete members. However, such an approach would make very little sense, given the fact that the structural model used (with the single truss elements for the walls) is incapable of capturing accurately the actual distribution of forces in the frame elements.

After applying the above procedure, a “capacity” curve was created for each record by plotting the PGA (intensity measure) on the vertical axis and the maximum inter-storey drift (damage measure) on the horizontal axis. Fig. 5(a) shows these curves for the 11 earthquake records that were used in this study for the 5-storey retrofitted building. Each IDA produces a curve that correlates the PGA of the selected earthquake record with the damage parameter, hence the IDR in our case. Therefore, for each structure we end up with 11 IDA curves, one for each record. Then, the median IDA curve is computed and is later used during the

Table 2 Materials used for thermal simulations

Material	Thickness (mm)	Thermal conduct. (W/m/K)	Density (kg/m^3)	Specific heat (J/kg/K)
Masonry	190	0.51	1500	790
Concrete	150	2.50	2400	1170
Mortar	3 or 6	0.87	1800	1090
Insulation	40	0.03	43	1210

economic loss evaluation process. This curve is given in Fig. 5(b).

2.3 Energy modelling

As in the case of seismic modelling, the energy modelling process with EnergyPlus^{TM} requires the creation of a model of the building to be analyzed. This includes the definition of its geometry, of all the surfaces that enclose each thermal zone as well as of the existing electrical equipment, lighting, hot water equipment etc. Afterwards, a yearly analysis can be run using weather files from the location where the building is located.

2.3.1 Simulation details

Initially, the thermal zones of the building to be analyzed are created in the EnergyPlus^{TM} model. Depending on the detail level of the simulation, the thermal zones can be separate rooms, apartments, floors or even the whole building. Higher level simulations produce more accurate results, are more intensive and are mainly used when detailed HVAC modelling is already included. On the other hand, lower level simulations are less intensive and more appropriate when global energy properties are needed (e.g., the total energy consumption of a building). In our case, the zoning of the buildings was done floor-wise, as only the total energy needs were needed to be calculated in each case.

Four different materials were defined and used in the program to model the various surfaces found in the building analyzed. These, along with all the necessary thermal properties are given in Table 2. Their combination/layering results in the formation of the construction surfaces (Table 3), which fully define the shells that enclose each thermal zone. The new layers added after the retrofitting are marked with an *R* at the end, to distinguish the initial and the retrofitted configuration.

In all thermal analyses it was assumed that the winter heating point was set at 20℃ (heating provided by natural gas) and the summer cooling point at 25℃ (cooling provided by AC units). Concerning the electrical equipment, lighting and the hot water needs, the values of 11 W/m^2, 8 W/m^2 and 3 W/m^2 were used respectively, typical for residential multi-family buildings (Grondzik *et al.* 2010). Finally, the typical value of 0.5 air changes per hour (ACH) was used to account for the need for air replacement.

2.3.2 Case studies

Yearly energy simulations were run for each building configuration before and after the thermal retrofit, accounting for four different locations. For that matter, four South European cities were selected, all located in Italy, due to the availability of EnergyPlus^{TM} data: Bergamo (average temperature 11.9℃), Florence (average temperature 14.2℃), Rome (average temperature 15.3℃) and Catania (average temperature 17.1℃). These were selected in order to investigate the thermal behaviour of the structures in a broad range of climates.

Table 3 Construction surfaces (from outer to inner) for thermal simulations

Ext. wall	Ext. floor	Ext. roof	Int. floor	Opening
Mortar/R	Slab	Covering	Covering	Glazing
Insulation/R	Covering	Insulation/R	Slab	Air gap/R
Mortar		Slab	Mortar	Glazing/R
Infill		Mortar		
Mortar				

Table 4 Annual energy consumption for 5-storey building in Florence

Heating needs (kWh)	170473
Cooling needs (kWh)	19512
Other equipment needs (kWh)	78851
Total energy consumption (kWh)	268835

After conducting the energy simulations, the yearly energy consumptions of the buildings were evaluated for each case and thus the exact energy needs for heating, cooling and other needs were calculated. For instance, the resulting consumption for the case of the 5-storey structure in Florence is given in Table 4. Moreover, Figs. 6(a)-6(b) show the heating/cooling needs and the indoor/outdoor temperature, respectively, for the same building-location combination. It is verified that the heating needs are high during the winter, whereas the cooling needs are high during the summer. It is also illustrated that the indoor air temperature variates differently during the year in comparison to the outdoor one.

3. Building economic loss estimation

For the economic classification of an existing building, the concept of the Expected Annual Loss (*EAL*) has been adopted, which is simply the money that the given building loses during a year. This measure is often expressed as a percentage of the structure's total value, thus an *EAL* of 1% means that, each year, the building loses 1% of each total value. A simple approach for the integrated assessment of energy efficiency and earthquake resilience was recently presented by Calvi *et al.* (2016), Bournas (2018a) and Mastroberti *et al.* (2018). Following an identical approach, the current study considers the total *EAL* as the sum of the annual energy consumption multiplied by the relevant energy unit costs (denoted EAL_E) and the expected annual seismic loss (denoted EAL_S) leading to the Eq. (2):

$$EAL_t \approx EAL_E + EAL_S \tag{2}$$

Whereas Eq. (2) assumes that EAL_E and EAL_S are

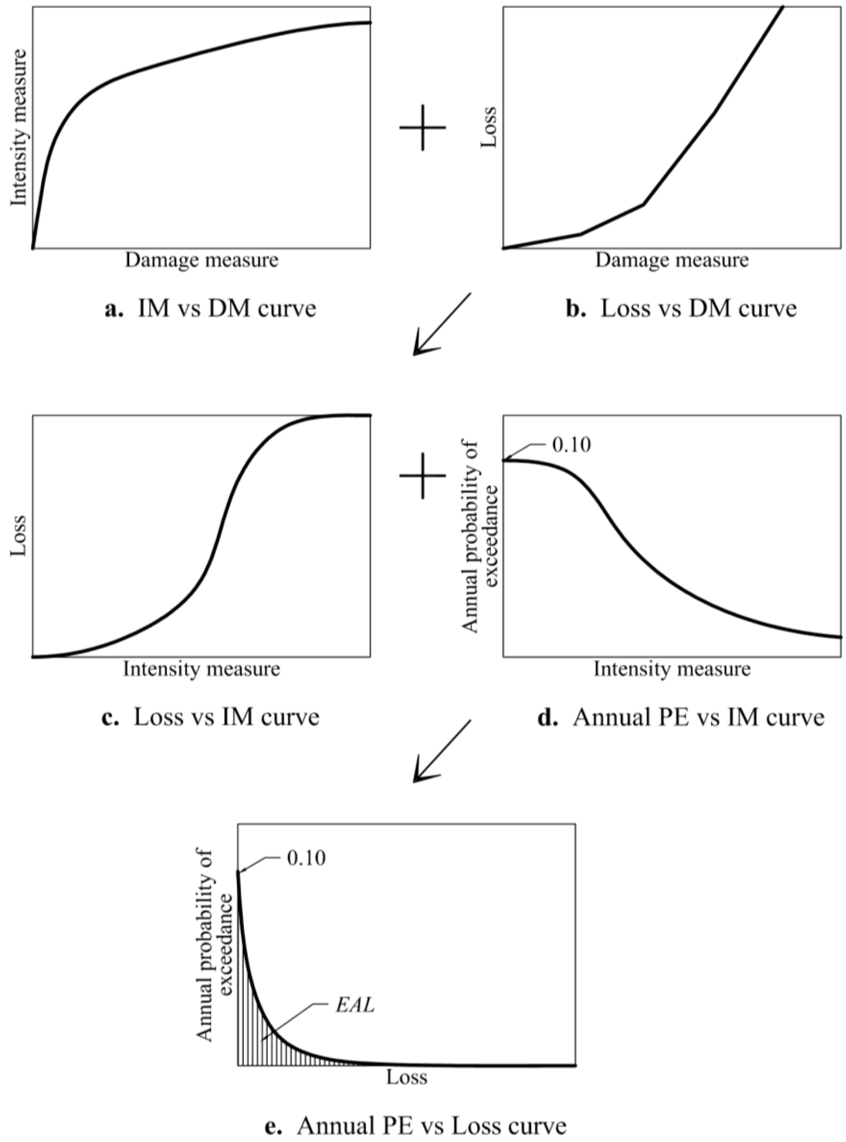


Fig. 7 Procedure to obtain EAL_S

uncoupled, seismic loading is expected to produce damage to the thermal envelope of the building, in addition to the structural members. However, since the EAL_S is mainly affected by the lower intensity earthquakes, as it will be demonstrated later, it is not expected that this approximation will have any negative impact on the accuracy of the final output.

3.1 Seismic loss

The estimation of the seismic loss is undoubtedly a difficult task to carry out reliably, although a number of techniques have been proposed over the years from the researchers' community worldwide. What is important to understand is that this task is closely related to the structural analysis methods used to characterize the building's earthquake resistance. One could, for instance, use a method of simple pushover analysis or a more sophisticated one that demands first the completion of advanced time-history simulations using detailed finite element models.

In this study, the earthquake simulation process included a large number of non-linear time-history analyses (NLTH), run on a rather simplistic finite element model. Therefore, the procedure to obtain the earthquake losses in our case should address the specific nature of the structural analysis that preceded this step. Using a highly advanced method to obtain these direct losses would be completely unnecessary, as the structural model itself would not be able to provide that very method with the input needed; and even if it could, that input would be at least unreliable. For that reason, it was decided to use the inter-storey drifts as those engineering parameters that would allow relating the analyses' results with the respective economic losses. Note that inter-storey drifts are able to capture structural damage in a global level, as was demanded in our case, where the finite element models were not so much refined to consider the structural damage element-wise.

The procedure that was followed to obtain the seismic EAL_S in the context of this work is summarized in Fig. 7.

First, a curve that correlates the intensity (IM, in this case the PGA) of the earthquake with the damage (DM, in this case the maximum drift) in the structure has to be constructed (Fig. 7(a)). This task has already been completed during the IDAs as explained in Section 2.2.2. Next, the selected damage measure (the maximum transient drift in our case) has to be correlated with the respective economic loss, expressed in this case as a percentage of the building's total value. This is achieved by using an existing loss model (that of HAZUS99 (1999) was used here) and mapping its damage states to actual values of the selected DM through pushover analyses with triangular lateral force distribution. Specifically, the HAZUS99 model prescribes 4 qualitative damage states which are given below along with the rules used to map them to the selected DM, that is the maximum inter-storey drift:

- *Slight* – Repair/Replacement cost 2%. Defined at the point where the linear behaviour is exhausted.
- *Moderate* – Repair/Replacement cost 10%.
- *Extensive* – Repair/Replacement cost 50%. Between the *slight* and *complete*, sharing equally the available space with the *moderate* damage state.
- *Complete* – Repair/Replacement cost 100%. Defined at the point where the base shear has dropped by 5%.

That way, a continuous curve is obtained that relates the loss with the DM (Fig. 7(b)). Finally, using the two curves obtained in the previous steps and noting that their horizontal axes are identical, one can create a new curve correlating directly the loss with the IM (Fig. 7(c)).

At this point, the location of the building has to be taken into account by relating the IM (that is the PGA or a_{gR}) to an annual probability of exceedance curve, which basically describes the site seismicity (Fig. 7(d)). Such a curve, according to Eurocode 8 (2004), can have the following simple form

$$H\left(a_{gR}\right) \approx k_0 a_{gR}^{-k} \tag{3}$$

In Eq. (3) $H(a_{gR})$ is the annual rate of exceedance, k can be taken equal to 3 and k_0 can be computed if the a_{gR} that corresponds to a probability of exceedance of 10% in 50 years is known; this value is known for every location according to each country's specific Eurocode 8 National Annex. In this function an upper limit of 0.10 is set, that practically translates to the fact that for a very frequent earthquake the loss is zero. Otherwise, for very small a_{gR}, the function would tend to infinity and the EAL_S would yield to infinity too. The limit of 10% adopted herein is a reasonable assumption that has been made by many researchers in the field (Calvi 2013).

If the above explained curve (Fig. 7(d)) is combined with the IM to loss function (see Fig. 7(e), again the horizontal axes are identical), a final curve correlating the annual probability of exceedance with the loss can be constructed. This curve intersects the vertical axis at the value of 0.10 because of the assumption made earlier; and once integrated, yields the EAL_S as a percentage of the building's initial value (see Fig. 7(e)). Since the integrated curve tends quickly to zero loss for an event with low annual probability of exceedance, that is a high intensity earthquake, it turns out that the EAL_S is more dependent on the lower intensity earthquakes which are more likely to occur. Therefore, any selected retrofitting scheme should apart from guarantying the structure's integrity and life protection during the design earthquake, also be able to ensure minimal damage for lower intensity ground motions.

3.2 Energy loss

The process for calculating the EAL_E is much more straightforward as the final energy needs per use (in kWh) can be directly obtained from the analyses conducted with EnergyPlus™ (see Table 4). Then, by multiplying the calculated energy consumption (in kWh) with the relevant energy unit prices, the yearly energy running cost of each building, and consequently the EAL_E (by dividing with the building's total value) are derived. The energy prices for Italy were taken from the online data of the European Commission (Eurostat 2018), whereas for the building prices considered in the case studies for the four Italian cities, market prices for existing buildings were obtained from Immobiliare (2018).

At this point, it is important to note that, when assessing a building from its energy point of view, the EAL_E index alone could lead to misleading conclusions. Comparing the energy consumption of two buildings, one located in Florence (building A) and the other in Catania (building B), it appears that building B consumes half the energy (per square meter) consumed by building A due to the different climate conditions (as is presented later in Table 7). However, given the fact that A is located in a city with double the real-estate prices of B, the two buildings have in the end almost identical EAL_E values. Therefore, although the *EAL* indexes can be used for assessing the combined seismic and energy retrofitting (see Eq. (2)), for a pure energy-based classification, the total consumption is a much more reliable parameter.

3.3 Retrofitting costs

In order to decide whether a retrofitting measure is economically feasible or when two or more such measures need to be compared, the retrofitting costs have to be computed. This task can be carried out with many levels of approximation, ranging from using simple global values (cost per m^2, per floor etc.) up to considering each and every detail of the retrofitting scheme and computing accurately the final cost.

Taking into account the general level of approximation used in earlier stages (structural modeling, loss evaluation etc.) of this work so far, it would be unwise to try to compute the retrofitting costs in a highly detailed manner. For that reason, it was decided to adopt similar retrofitting costs with those presented in Bournas (2018a), Mastroberti *et al.* (2018), which were estimated after consulting construction companies in Greece and Italy that have applied both TRM jacketing and thermal insulation in structural strengthening and energy retrofitting projects independently; these costs are summarized Table 5 and include both the materials and the labour.

With reference to Table 5, the energy retrofitting cost comprises both the addition of external insulation and the

Table 5 Retrofitting costs

Retrofitting scheme	Cost
Energy retrofitting (€/m2)	80
Seismic retrofitting (€/m2)	60
Integrated approach (€/m2)	105

Table 6 EAL_s (%) values before and after seismic retrofitting

PGA-g	EAL_s initial			EAL_s retrofitted		
	2s	5s	5sp	2s	5s	5sp
0.1	0.16	0.21	0.30	0.07	0.15	0.17
0.2	0.26	0.35	1.35	0.14	0.28	0.29
0.3	0.43	0.63	3.23	0.21	0.46	0.43
0.4	0.66	0.93	4.66	0.33	0.67	0.62
0.5	0.93	1.27	6.64	0.47	0.89	0.82

substitution of the fenestration surfaces. On the other hand, the seismic retrofitting cost takes into account the TRM wrapping of the outside walls of a structure and is only applied to those floors that are retrofitted. However, the most important conclusion drawn from Table 5 is that the integrated retrofitting is roughly 25% cheaper than the energy and the seismic applied at different times. This happens mainly because certain expenses like labor, scaffolding etc. are paid only once.

3.4 Pay-off time evaluation

One last important characteristic of every retrofitting scheme, that defines whether it is economically feasible or not, is its pay-off time. This is simply the time needed for the owner to take back their initial investment, considering the yearly savings of the applied scheme realized through the reduction of the total *EAL*. This parameter can also be used for the economic comparison of different retrofitting techniques and help the engineer decide which one to implement, provided that all the options guarantee (nearly) the same degree of upgrading.

4. Results and discussion

After applying the procedures explained in Section 3, the *EAL* (seismic and energy), the retrofitting costs and the pay-off times were calculated for all the building configurations and possible locations.

Table 6 presents the EAL_S values for all the building configurations (including the retrofitted ones) and accounting for various site seismicities, from 0.1 g to 0.5 g (refer to Fig. 2(b) for the notation 2s, 5s, 5sp). As it can easily be seen, the retrofitting technique employed can indeed lower the EAL_S values quite considerably, therefore protect the inhabitants and also save money from reconstruction costs for the owners by minimizing the structural damage in the case of an earthquake. Moreover, the higher the seismicity, the higher the drop in the EAL_S due to the application of the proposed retrofitting scheme, implying a faster pay-back time for the initial investment.

Table 7 Annual energy consumptions in kWh/m^2 for all cases

City	2-storey		5-storey		5-storey pilotis	
	Initial	Insul.	Initial	Insul.	Initial	Insul.
Bergamo	343.9	187.8	280.3	168.4	338.9	182.4
Florence	275.6	156.3	224.0	139.8	267.3	149.6
Rome	226.1	131.0	183.6	118.1	217.6	125.3
Catania	174.7	107.6	143.3	99.6	166.3	103.9

Considering the case of the buildings used in the case studies located in an area that has a PGA of 0.3 g (probability of exceedance 10% in 50 years or return period 475 years) and a real-estate value of 2500 €/m^2, it turns out that, in absolute values, each year the 2-storey building would be saving 2640 €, the 5-storey 5100 € and the 5-storey with pilotis 84000 €, after applying the proposed strengthening scheme.

The big difference that is observed for the 5sp configuration reflects its considerably higher initial seismic vulnerability prior to its strengthening, due to the soft-storey response. Buildings without infills in the ground storey (pilotis type) are highly irregular height-wise as both the strength and the stiffness of the first storey is significantly lower than that of the above ones. Consequently, the columns of the first storey need to deform much more – to achieve the same level of lateral top displacement – hence the ductility demand increases dramatically. That is why the observed failure mode of this type of buildings is the complete destruction of the ground floor, with the rest of the structure being practically intact. A very effective way to avoid this behaviour is to provide new stiff and strong elements so as to increase the first floor corresponding resistance and stiffness thus minimizing the irregularity in height. The proposed technique can do exactly that and that is the reason behind the dramatic drop in the EAL_S of the 5sp configuration.

In Fig. 8, the time-histories of the drifts are plotted for the 5sp configuration, before and after retrofitting. It is clear that the pilotis configuration leads to concentration of damage only in the ground floor, as there is permanent, irrecoverable drift in it, l*et al*one that the drift values of the above stories are comparably insignificant. This outcome is in accordance with the conclusions found in the work of Favvata *et al*. (2013). On the other hand, in the retrofitted building, the drifts of all 5 stories are of the same magnitude during the earthquake, meaning that the damage is successfully distributed in the whole structure rather than just a part of it. For the other cases, 2s and 5s namely, the benefit of the retrofitting is attributed only to the increase of the structure's lateral stiffness and resistance leading in reduced drifts in the retrofitted buildings without basically changing the overall structural behaviour.

Table 7 provides the total energy consumptions for each building configuration and location. As it can be seen, the selected retrofitting scheme can effectively reduce the energy consumption of the buildings considered. This reduction varies between 30% and 46% and could be even higher if a more extended retrofitting scheme had been employed (e.g., thicker insulation material, replacement of

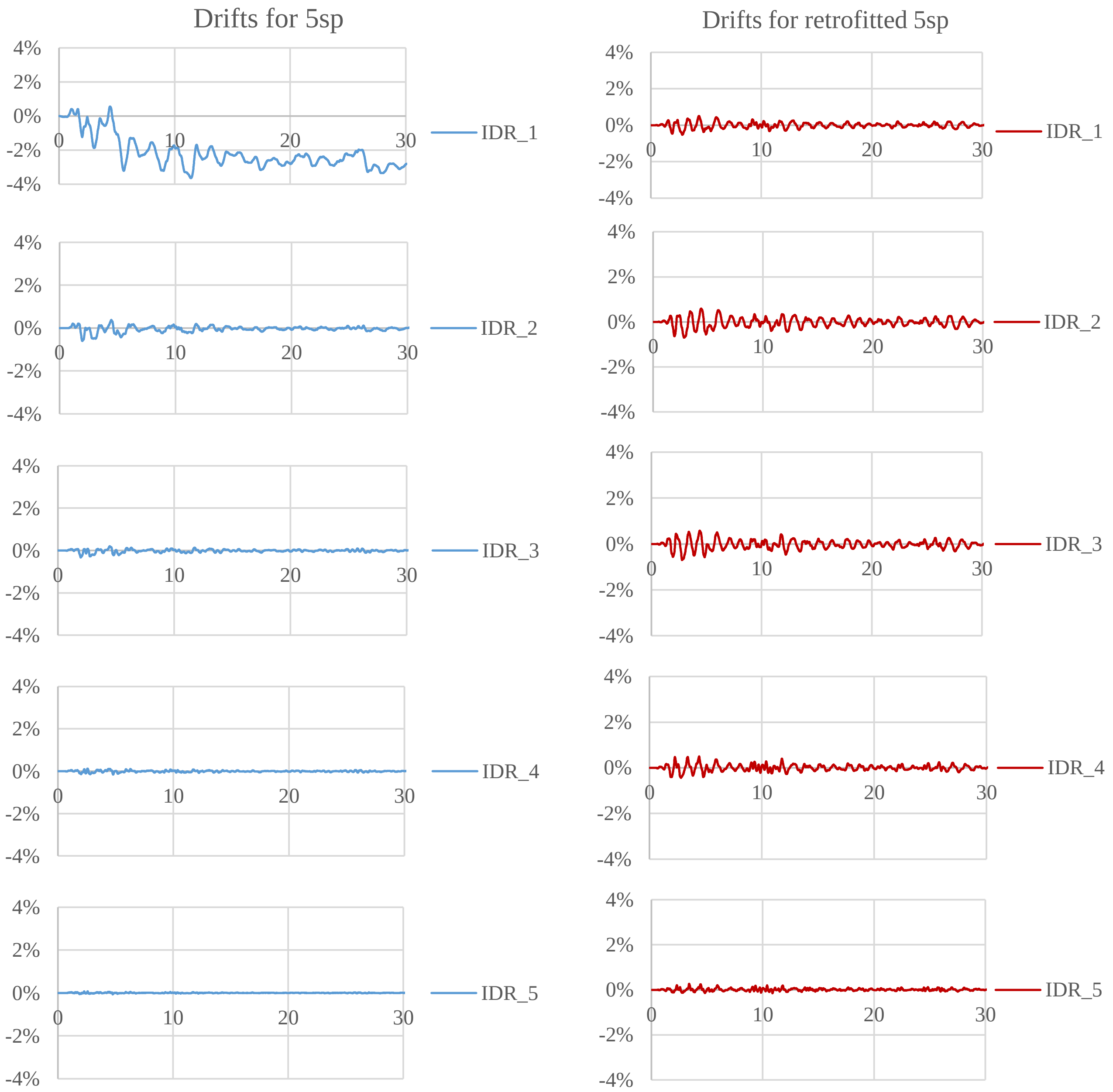


Fig. 8 Time-histories of inter-storey drifts, 5sp configuration, El Centro earthquake

Table 8 Pay-off times in years for each city-building-scheme combination

Scheme	Bergamo			Florence			Rome			Catania		
	2s	5s	5sp	2s	5s	5sp	2s	5s	5sp	2s	5s	5sp
Energy	5.9	8.5	7.7	7.5	11.0	10.1	9.0	13.8	12.7	11.9	19.7	18.0
Seismic	30.1	34.2	12.4	17.2	18.3	4.1	18.2	19.8	3.8	33.8	43.1	3.0
Integrated	6.8	9.3	7.0	7.4	10.1	5.1	8.6	12.2	5.3	12.4	19.4	4.9

the mechanical equipment). The conversion of the consumptions to EAL_E can be carried out easily if the energy costs and building values are known. However, when it comes to the energy classification of a building, the EAL_E measure provides no essential information, as it relies heavily on the building's value. With reference to Table 7, the buildings in Bergamo and Catania have a difference roughly equal to 2 to 1 in their energy consumptions. However, since the Bergamo real-estate prices are twicethose in Catania, the EAL_E values are in the end almost the same, therefore not able to reflect the much higher need for energy upgrading in the city of Bergamo.

Finally, Table 8 summarizes the pay-off times in years for each building-location combination in the case of energy, seismic or combined seismic plus energy retrofitting. In this evaluation, the actual PGAs for the four selected Italian cities were used as obtained from a WebGis application of the Italian National Institute of Geophysics and Volcanology, which is publicly available (Interactive Seismic Hazard Maps 2007). These were 0.11 g, 0.13 g, 0.14 g and 0.21 g for the cases of Bergamo, Florence, Rome and Catania, respectively.

Table 8 reveals an important aspect of the retrofitting schemes, once they are compared to each other. Specifically, consider the case of energy retrofitting alone and that of the integrated approach – this is the comparison that makes the most sense because building owners are more likely to invest in a sole-energy upgrading, thinking that they will get their money back in a shorter amount of time as the benefit is much more obvious in this case. As one can see though, in all the columns where the last cell has a background shading, the integrated retrofitting scheme actually has a shorter pay-off time than that of the energy retrofitting scheme. In other words, the initial investment made by the building owner will be returned faster, if they upgrade their property both energetically and seismically rather than enhancing it only in terms of its energy efficiency. The same also holds true for the comparison between the integrated and the sole-seismic retrofitting, in which case the difference is much higher and more favourable for the integrated approach in most cases. Only for the structure with the pilotis configuration, the seismic upgrading scheme seems to be more efficient than the integrated one, mainly due to the increased vulnerability of this type of buildings.

Needless to say, the integrated retrofitting scheme demands a somewhat higher initial investment. According to this study, for the 2-storey building the energy retrofitting scheme costs 38400 €, while the integrated costs 50400 € (31% more expensive). For the 5-storey, the respective values are 96000 € and 120000 € (25% more expensive). Therefore, taking into account the faster return period, it is certainly worth it, for any old building owner, to invest a slightly higher initial amount of money and apply an overall retrofitting to their structure. That way, the upgraded building will be much safer and economical to live in and of course, will have a much smaller energy footprint. At the same time using an environmentally sustainable, integrated solution, as the one proposed in this work, is of extreme importance nowadays.

5. Conclusions

Through a number of case studies and a simple methodology which involves seismic, thermal and economic loss analyses, the paper proves that the integrated seismic (using textile-based composites) and energy retrofitting of a structure is an effective approach. The results demonstrate that, in most cases, it is economically more effective to follow the integrated approach than upgrading a building only seismically or in terms of energy, as the initial investment is paid back faster. Therefore, for every structure located in a seismically active area (say PGA>0.10 g), the integrated approach should be preferred for a number of reasons. First, there are significant savings in money terms, as the labor and scaffolding expenses are paid only once. This results in a roughly 25% lower initial investment than the case of applying the seismic and energy upgrading separately. Moreover, the building is "armoured" against future seismic events and the energy investment is safe. Otherwise, if energy retrofitting had been applied only, then a possible destructive earthquake would make this investment practically useless. Last, but not least, using the *EAL* logic, it is proved to be economically more efficient to follow the integrated approach, when the structure at hand is situated in a seismically active territory.

Clearly, the integrated approach demands a somewhat higher initial investment than a sole seismic or energy upgrade, which might not always be available. For that reason, it is highly recommended that the states should consider funding up to a certain point such retrofitting efforts, in order to minimize the existing infrastructure's CO_2 footprint and armor it against future earthquake events.

The work presented in this paper should be considered as a "proof of concept" one and not as a detailed investigation on the topic; hence the results should be used with caution and in a rather qualitative sense. Future work should be directed in analyzing different building configurations, possibly using more sophisticated tools, and located in different thermal zones.

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